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The optimal research and development portfolio of low-carbon energy technologies: A study of China

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To support decision-making for an optimal portfolio strategy for low-carbon energy technology research and development (R&D), this study proposes a dynamic two-stage stochastic programming model, taking into account both the uncertainty of technological change and damages of climate change. Based on China's economic and technology level and expert elicitation, an R&D investment portfolio strategy looking at three low-carbon technologies (carbon capture and storage [CCS], solar photovoltaic [PV], and nuclear), including nine projects, is investigated through the proposed model. The optimized results show that the optimal R&D technology portfolio is robust to different levels of risk in climate damage. However, the total social costs for the optimal R&D technology portfolio is lowest in the medium risk of climate damage scenario. Under different opportunity costs, the composition of the optimal R&D portfolio varies. However, projects for each of the three technologies always constitute the optimal R&D portfolio. Furthermore, the implication is that a technology synergistic R&D strategy is conducive to enhancing the level of CO_2 abatement and reducing the total social cost.

1. Introduction

Climate change has become one of the most important issues in the world. Increasing GHG emissions in the atmosphere caused by human activity, such as fossil fuel combustion, has been identified as a primary cause of ongoing climate change (IPCC, 2014). Although the growth in global GHG emissions has slowed in the last two years (Peters et al., 2017), the issue of climate change remains a critical challenge based on the longevity of its effects, its global nature, and deep uncertainty. Some measures have proven to be effective in reducing energy-related GHG emissions, including improving the efficiency of energy use and the development of carbon-free renewable energy, and adjustment the industrial structure of high fossil fuel consumption and high carbon-based. However, no matter which method is chosen, a rapid change to low-carbon energy is necessary to inhibit climate change in a way that is consistent with sustainable economic growth and current policies (Blanford, 2009; Wang et al., 2018; Yu et al., 2015). The innovation of new clean technologies has also become a focus of discussion in recent negotiation on climate change (Suzuki, 2015). In general, learning by doing and investment in research and development (R&D) are two basic ways to achieve technological change. Learning by doing provides some insights, but has key weaknesses and requires information about past performance. Since many of the technologies do not yet exist in commercial form, there is no past performance on which to base an estimate (Nordhaus, 2009). Moreover, learning by doing usually takes a long time to achieve a technology breakthrough as it is based on the experience of the production and natural diffusion of technologies. Therefore, it is difficult to cope with the severe challenges of global warming. On the other hand, R&D can have a significant effect on improving the performance of low-carbon energy technologies (Barron and McJeon, 2015; Hellsmark et al., 2016) and has been found to be cost-effective (Corderi and Lin, 2011). Moreover, the development of new technologies and the improvement of existing ones can enhance policy responses to challenges like climate change.

Several analyses of the role of investment in R&D have been conducted, with each focusing on a single group of low-carbon energy technologies to assess climate change impacts. By

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combining expert elicitations and economic modeling, the impact on climate change of R&D in individual technology has been investigated in areas such as solar photovoltaic (Baker et al., 2009a), carbon capture and storage (CCS) (Baker et al., 2009b; Nemet et al., 2015), nuclear power (Baker et al., 2008), automobile batteries (Baker et al., 2010), and boiler technologies (Park et al., 2017). These studies have shown that the availability of the technology plays a vital role in feasibility and cost when facing the challenge of stringent climatic targets. However, this individual technology research limits the insights that such studies can offer about the interdependencies among technologies. Multi-technology assessments can address environmental and technological interdependency issues (Barron, 2015). The technology portfolios are powerful tools in that they allow R&D projects to be analyzed in a systematic manner (Cluzel et al., 2016). Therefore, when constrained by a given budget and facing a set goal of carbon emissions targets, it is critical to make a decision on the R&D strategy for a portfolio of low-carbon energy technologies. However, in such a discussion, it is not clear what technologies the portfolio should contain.

A strategy for an R&D portfolio of technologies involves significant uncertainty, which cannot be avoided. Technology breakthrough requires risky efforts in R&D because of its high uncertainty and capital intensiveness (Arvanitis et al., 2017; Marangoni et al., 2017). For example, for a particular R&D program, success or failure is uncertain, and the degree the program will meet or exceed the set goals is also uncertain. Furthermore, there is a significant uncertainty that experts attach to R&D investments as well as huge disagreement among such experts (Baker et al., 2015a; Marangoni et al., 2017). A number of researchers have developed various models to deal with a portfolio strategy for R&D technologies taking into account uncertainty. Among them, the integrated assessment model (IAM) is the most common approach to dealing with uncertainty within portfolio optimization. For instance, by running an IAM, Blanford (2009) calculated the optimal portfolio by linking R&D investments to a probability distribution over alternative outcomes. Lemoine and Traeger (2014) evaluated optimal climate policies in a dynamic integrated model of climate and the economy (DICE), a widely accepted IAM, including the endogenous possibility of climatic tipping points, their welfare implications, and learning their trigger temperatures. Through a large IAM, Baker et al. (2015b) estimated the economic interactions of five technologies, considering four sets of probabilistic distributions from experts. Beyond the IAM, other types of energy-economic models have also been proposed to obtain an optimal R&D portfolio of low-carbon energy technologies. For instance, Bistline (2016) developed a stochastic R&D portfolio management framework to determine the optimal investment levels for individual programs subject to a budget constraint, using an empirically grounded model of R&D-driven innovation with uncertain returns. Based on the MARket ALLocation (MARKAL) model, Chan and Anadon (2016) proposed a sampling and optimization strategy to calculate optimal R&D portfolios by evaluating different metrics (such as system benefits, technology diffusion, and uncertainty around outcomes) relevant to an energy R&D portfolio. Within the framework of a bottom-up partial equilibrium model, Usui et al. (2017) investigated the dynamic technology transition in the Japanese electricity sector and the optimized R&D investment schedule for each renewable. These studies have focused on the uncertainties of low-carbon energy technologies themselves and the uncertainties of their R&D outcomes but have not included the uncertainties of damage caused by climate change. The potential damages from climate change are also deeply uncertain; in particular, how will an extra ton of carbon emitted today impact a stream of damage in the future (Baker and Solak, 2011)? The marginal damage of climate change is critical to climate policy formulation. Further, the damage degree of climate change (degree of risk) can also affect technological change (Baker and Shittu, 2008; Bistline and Weyant, 2013; Yu et al., 2017).

Therefore, recently, several studies have explored the optimal R&D portfolio of low-carbon energy technology, taking into account the uncertainty of both technological change and damages caused by climate change. For example, considering the uncertainty of future technological success and climate change, Baker and Solak (2014) investigated an R&D portfolio of US energy technologies (nuclear, solar PV, and CCS). They found that the optimal technology portfolio was fairly robust to different specifications of climate uncertainty. Similarly, Barron et al. (2014) examined the impact of US grid integration costs on the optimal R&D portfolio that minimized the cost of climate change. Their findings implied that the importance of getting grid integration costs right depended on the specific question being asked. By considering uncertainty in technology improvement and climate damages, Olaleye (2016) proposed a multi-model framework to determine the optimal allocation of R&D funds to a technology portfolio in the US. The general view of these studies suggests that the optimal portfolio of R&D technology mainly depends on how the modeling of the technology changes based on assumptions and data. However, these studies are all focused on a combination of low-carbon energy technologies in the US. No research investigates the investment decisions for a portfolio of R&D technology in China.

As the world's largest carbon emitter, China is facing enormous pressure to reduce emissions. Yet, China's low-carbon energy technology is lagging behind the developed countries. Therefore, considering the level of China's energy technology and carbon emissions, it is important that an optimal R&D portfolio strategy for low-carbon energy technology be studied in China as well. First, such a study would help clarify the relationship between various low-carbon energy technologies and the costs and effects of carbon emissions reduction in China. Second, obtaining the optimal investment portfolio would provide the support needed for decisions regarding formulating R&D investments while considering the committed emissions goal of re-education.

Regarding these, in the present study, we focus on China's low-carbon energy technology R&D portfolio for the first time, taking into account the uncertainty of technological change and of climate change damage. In our study, the carbon abatement cost function and climate damage cost function are introduced to characterize technological change and climate change, respectively. Furthermore, based on the expert elicitations, a two-stage stochastic model is developed to cope with the uncertainty of technological change and of climate change damage. According to the results of the modeling, we try to answer, for given budget constraints, how should the government's investment funds be allocated to different R&D projects? In other words, what is the optimal R&D technology portfolio?

The contributions of our study are as follows: First, parameter settings take full account of China's economic and technological level. For example, compared with the US, China needs more investment in CCS R&D based on a difference in technical advancement. Second, by simultaneously considering the uncertainties of technology breakthrough and climate damage, a budget constrained model (BCM) and an overall optimal model (OOM) are developed to solve the optimal portfolio of R&D technologies for a given budget and the minimized expected social cost, respectively. Finally, the swarm intelligent optimization solver, MIDACO (mixed integer distributed ant colony optimization), is applied to solve the proposed models, which can simply and efficiently obtain the solutions without many mathematical transformations.

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