Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

A dynamic programming model for environmental investment decision-making in coal mining

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HIGHLIGHTS

- A DP model is proposed for investment decision-making of environmental projects.
- The model can obtain the optimum investment strategy to meet the emission standard and to minimize costs.
- The results show that the model is effective and applicable for investment decision-making.

ARTICLE INFO

Article history:
Received 1 May 2015
Received in revised form 17 July 2015
Accepted 29 September 2015
Available online xxxx

Keywords:
Coal mine
Pollution treatment
Dynamic programming
Investment decision-making

ABSTRACT

Coal is the widespread fossil fuel on earth. It provides the necessary material foundation for economic development of a country. However, coal mining activities cause a lot of environmental impacts that are hazardous to the health of citizens in mining regions and place costs on the government. According to government laws and regulations, coal mines should invest in related pollution treatment projects to meet the emission standards. How to allocate the limited resources among a set of pollutant treatment projects to minimize the total losses, including penal loss and vacancy loss, from an investment perspective is a typical decision-making problem. Therefore, the present study proposed a discrete dynamic programming procedure to provide an effective solution for decision-making in treatment project investment. Furthermore, a case study involving the Laojuntang coal mine of Zhengzhou Coal Industry (Group) of China on the treatment project investment problem was implemented using the proposed model. The results demonstrate that the proposed model is effective and applicable for environmental investment decision-making at a typical coal mine in terms of minimizing the total losses.

1. Introduction

As the most abundant fossil fuel on the planet, coal provided around 29.0% of the global primary energy need and generated about 40.4% of the world's electricity in 2012 [1]. Coal mining is one of the core industries that contribute to the economic development of a country. However, coal production usually causes serious damage to the environment, including impacts on groundwater quantity and quality, land subsidence, mining waste stockpiling, land occupation and other effects [2,3]. Take China as an example. The production of coal was 3.6 billion tonnes in 2013, accounting for up to 45.5% of global yields [1]. As a result, large quantities of mining waste were produced, including coal gangue, coal sludge, fly ash, coal mine drainage and coal bed methane (CBM) [4]. Statistics show that the total emissions of industrial waste water were 1.42 billion tonnes, waste gas reached 32.49 billion m^3 and solid wastes reached 385.37 million tonnes in 2012 [5]. Furthermore, the annual leaked emissions of CBM amounted to 15 billion m^3 [6]. It is generally argued that serious adverse environmental impacts and damages may be caused by coal mine waste, including interference with groundwater quantity and quality, land subsidence, creation of geological hazards, visible and esthetic issues, damage to infrastructure and potential ecological havoc [7,8]. An area of about 30 km^2 of subsidence is caused by underground coal mining every year [9]. And eventually these environmental damages will become constraints to economic development.

To protect the ecological environment of coal mining areas, the main coal-producing countries such as China, the United States, India and Australia issued a series of special laws and regulations

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http://dx.doi.org/10.1016/j.apenergy.2015.09.099
0306-2619/

Please cite this article in press as: Yu S et al. A dynamic programming model for environmental investment decision-making in coal mining. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.09.099

for the coal industry. For example, the Chinese government released the *Emission Standard for Pollutants from the Coal Industry (GB 20426-2006)*. In particular, in 2010, China's National Development and Reform Commission promulgated *The 12th Five-Year Development Plan for the Coal Industry* and *Opinions of Energy Conservation and Emissions Reduction Work in the Coal Industry*. The plan clearly states that by the end of 2015, China needs to reach the following targets: a national raw coal feed cleaning rate of more than 60%; a comprehensive utilization of solid wastes such as coal gangue rate of more than 75%; an extraction and utilization of methane rate of more than 55%; a mine water utilization rate of more than 80%; and a soil reclamation rate of more than 50%. The document also states that all large coal companies should meet the prescribed pollutant emission standards. If the emissions do not meet the requirements of the laws and regulations, the coal companies will be fined or forced to shut down. This loss may be called "penal costs." Clearly, coal mines should invest in pollution treatment projects, environmental technologies or waste recycling utilization procedures to avoid such penalties. However, if the treatment project is introduced too early, despite avoiding the fine, it will cause investment capital occupation loss as the pollutant generation rate is lower than the equipment treatment rate. The loss is then called "vacancy costs." Constrained by the amount and types of pollution, the treatment capacity of projects and capital limit, coal mines should make an appropriate decision to minimize the total investment cost of pollutant treatment projects. Obviously, this is a typical optimization problem of investment decision-making.

Different mathematical models or methods have been proposed to deal with the optimization problem of decision-making in environmental protection project investments. For example, Lin et al. applied the real option approach to evaluate the optimal environmental investment decisions under economic and ecological uncertainty [10]. Higgins et al. explored a multi-objective integer- programming model for environmental investment decision-making [11]. Myšková et al. discussed the decision-making in relation to environmental investments in waste water treatment plants using TOPSIS (the technique for order of preference by similarity to ideal solution) [12]. Kusi-Sarpong et al. introduced a multiple criteria evaluation of green supply programs using a novel multiple criteria approach that integrates rough set theory elements and fuzzy TOPSIS for the mining industry [13]. Moreover, Jaraite et al. developed a regression model identifying to investigate how environmental expenditure and investment of Swedish industrial firms responded to climate policies, such as the European Union's Emission Trading System (EU ETS) and the Swedish CO_2 tax, directed to mitigate air pollution [14]. These studies provided good solutions for the real decision-making in environmental project investments. However, decision-making is a multistage process aimed at finding a sequence of decisions that maximize (or minimize) an appropriately defined objective function such as costs, losses or risks. The dynamic programming (DP) procedure is a good candidate for handling this type of decision-making problem due to its dynamic nature, and is more effective than using linear programming or nonlinear programming alone. DP is a numerical algorithm based on Bellman's optimality principle [15] that finds the control law, which provides the global minimum value for the given objective function while satisfying the system constraints. In the modeling, DP converts a complex problem with multiple decision goals and limited resources into a sequence of interrelated subproblems arranged in stages, so that each subproblem is more tractable than the original problem.

The DP model has been widely applied to make optimal decisions on various decision-making problems, such as wastewater treatment system optimization [16], optimal well selection strategy [17], and the portfolio of IT projects' problem decision-making [18]. There are also several studies applying DP to find global optimum decision-making in energy systems. These studies can be divided into three broad categories: (1) DP optimization decision-making in electrical distribution systems. For example, Khalesi et al. applied dynamic programming to discover the optimal locations to place distributed generations (DGs) in a distribution system to minimize the power loss of the system and enhance the reliability and voltage profile [19]. Ganguly et al. presented a DP to solve the multi-objective optimization planning of electrical distribution systems [20]. Marano et al. applied the DP technique to the optimal management of a hybrid power plant, which consists of compressed air energy storage (CAES) coupled with a wind farm and photovoltaic panels, taking into account energy, economic and environmental aspects [21]. (2) DP optimization applications in energy storage systems management. This kind of study can be represented as follows. Liang et al. proposed a long-term operation optimization model of a Pumped-Hydro Power Storage (PHPS) station based on approximate DP [22]. For deriving the best configuration and energy split strategies, Song et al. utilized the DP approach to deal with the integrated optimization problem of a hybrid energy storage system that includes a battery and a supercapacitor for an electric city bus [23]. To achieve the optimal energy allocation for the engine-generator, battery and ultracapacitor of a plug-in hybrid electric vehicle, Zhang and Xiong employed a DP model to develop suboptimal control strategies for different driving blocks [24]. Furthermore, Fares et al. applied DP technique for optimizing fuel cell hybrid vehicles [25]. (3) DP optimal decision-making in oil stockpile strategy. Wu et al. presented a dynamic programming model to determine the optimal stockpiling and drawdown strategies for China's strategic petroleum reserve under various scenarios, focusing on minimizing the total cost of reserves [26]. Bai et al. applied DP to optimize a stockpile strategy for China's emergency oil reserve by minimizing stockpiling costs, including consumer surplus as well as crude acquisition and holding costs [27]. Besides these three categories, Škugor and Deur proposed a DP optimization method for aggregate battery charging for an electric vehicle fleet. They claimed that the DP method could lead to global optimal results for the applications [28]. Li et al. proposed a DP model for optimal control of a wave energy converter [29]. Although DP is very popular in many decision-making issues, less attention has been drawn towards dealing with environmental investment decision-making.

Therefore, our objective in this paper is to develop a multistage discrete dynamic programming procedure for investment decision-making in coal mine pollution treatment in China. There are two reasons for us using the DP method to solve the environmental investment decision-making problem in coal mining. First, the decision-making on investment in pollutant treatment projects has obvious dynamic stages, which decision of each stage constitutes entire decision-series of the problem. Second, it can always be guaranteed that DP will find the optimal global solution [21]. In the proposed procedure, the DP transforms the complex investment decision-making problem into a sequence of interrelated subproblems arranged in stages while considering the constraints of the amount and types of pollution as well as the treatment capacity of projects and capital limit. Furthermore, a case study of a pollution treatment project investment problem at the Laojuntang coal mine of Zhengzhou Coal Industry (Group) is implemented.

2. Problem statement

2.1. Pollutants and their treatment of coal production

The activities of coal production and utilization include mining, preparation and combustion of coal-fired boilers for heating.

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