Energy Economics 34 (2012) 1058–1063

Contents lists available at SciVerse ScienceDirect

Energy Economics

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

Optimal path for China's strategic petroleum reserve: A dynamic programming analysis

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ARTICLE INFO

Article history:
Received 1 February 2010
Received in revised form 1 June 2011
Accepted 30 August 2011
Available online 7 September 2011

JEL classifications:
C61
Q41

Keywords:
Strategic petroleum reserve
Dynamic programming
Petroleum acquisition strategy
Stockpile

ABSTRACT

This paper proposes a dynamic programming model to explore the optimal stockpiling path for China's strategic petroleum reserve before 2020. The optimal oil acquisition sizes in 2008–2020 under different scenarios are estimated. The effects of oil price, risks and elasticity value on inventory size are further investigated. It is found that the optimal stockpile acquisition strategies are mainly determined by oil price and total inventory costs. While oil supply disruption is not considered, China's optimal stockpile acquisition rate increases from 19.2 to 52 million barrels from 2008 to 2020. If an oil supply disruption occurs, the oil acquisition rate will be reduced significantly. However, it may not be a good strategy to interrupt oil reserve activities in order to minimize the total costs for the entire planning period.

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1. Introduction

China's fast economic growth over the past three decades greatly boosted its demand for oil consumption. According to NBSC (2008), China's annual oil consumption was 360 million tons in 2008 and more than 50% of that relied on imports. Compared to the 169 million tons in 1995, this figure has become doubled in thirteen years. It is estimated that till 2020 China's annual oil demand will be about 560–600 million tons, while the annual domestic oil supply is only about 200–220 million tons. The oil supply-demand gap will reach 340 to 400 million tons, which implies that over 60% of the oil demand will have to be dependent on imports. China's growing dependence on overseas oil supplies, which are mainly from the Middle East and West Africa, has resulted in a major concern about its future oil supply security. This concern was further enhanced by the insufficient commercial oil storage capacity in China.

In order to safeguard its oil supply security, China government has also established its strategic petroleum reserve (SPR) by following international practices. SPR is an emergency oil storage maintained by a country to ensure its energy and economic security (Wei et al., 2008; Wu and Wei, 2009). It is generally agreed that SPR is an effective and powerful measure against the negative effects due to oil supply interruption. The largest SPR holder in the world is the United States with a reported capacity of 727 million barrels (Taylor and van Doren, 2005). Japan is the second largest SPR holder with a capacity of 579 million barrels in 2003. China's target is to build a SPR equivalent to 100 days' net oil imports by 2020. Since earlier 2004, China government has been preparing for the establishment of its SPR. By the end of 2008, all the four stockpile bases of its first SPR project had been finished with a capacity about 1000 to 1200 million tons (Xue and Qiao, 2009).

Owing to the practical significance of SPR, researchers have begun to study SPR issues with modeling techniques since the first world oil crisis. Several earlier studies, e.g. Nordhaus (1974) and Tolley and Wilman (1977), proposed to use the two-period model to identify a single "optimal stockpile size". By considering the mutual influences among different decision-makers, several researchers have also employed game theoretical models to study the SPR issue. Balas (1981) developed a short-run game between oil importing nations and a politically motivated cartel that takes advantage of disruptions to inflict economic losses on importing nations. Hogan (1983) established a Stackelberg game model for examining the interactions between two oil consuming countries. Murphy et al. (1987) proposed a discrete time Nash game for modeling the inventory interactions between two nations or two aggregates of nations. Some discrete models, e.g. decision tree, have also been used for quantifying the optimal SPR. For instance, Samouilidis and Berahas (1982) established a decision tree model considering both crude oil and refined oil

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0140-9883/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.eneco.2011.08.019

inventories. Recently, Wei et al. (2008) developed a decision tree model to analyze China's optimal stockpile size under different scenarios.

Some non-linear optimization models have also been proposed for solving the SPR problem. Kuenne et al. (1979) used an optimization model, which includes a GNP response function and crude oil supply reductions, to determine the optimal drawdown trajectories for SPR during an embargo. Hubbard and Weiner (1986) estimated an equation for private oil inventory behavior in the United States and discussed public–private interactions in stockpiling. Zweifel and Bonomo (1995) developed an optimal reserve model that takes into account multiple risks for oil and gas. In addition, the optimal stockpile size has been qualitatively analyzed in many previous studies including Kata (1981), Jenkins-Smith and Weimer (1985), and Taylor and van Doren (2006).

As a well established operations research technique, dynamic programming (DP) has also gained popularity in estimating the optimal SPR. Teisberg (1981) developed a DP model to estimate the optimal acquisition and sale strategies for the SPR of the United States. Chao and Manne (1983) extended the study by Teisberg (1981) to the case with a broader conception of oil disruption cost and the state space. Oren and Wan (1986) proposed a stochastic DP approach to quantifying the optimal size, fillup and drawdown rates for the SPR of the United States under various assumptions. Recently, several studies have also used DP to study China's SPR. For example, Wu et al. (2008) quantified the impact of the uncertain in world oil prices on the optimal stockpile acquisition strategies of China's SPR for the periods 2007–2010 and 2011–2020. Zhang et al. (2009) further analyzed the optimal size of China's SPR and the best acquisition and drawdown strategies.

The above studies on China's SPR mainly dealt with the estimation of the optimal SPR size or acquisition and drawdown strategies. Once the inventory size planned and the time limit are specified, the issue on how to stockpile must be addressed. As described earlier, China's SPR target is to have an oil reserve equivalent to about 100 days of net imports before 2020. What kinds of reserve strategies should China follow to realize its SPR objective in a cost-effective manner within the specified time? Which factors will affect China's oil reserve strategies? How to affect? This paper attempts to answer these questions by exploring China's optimal stockpiling path for attaining its SPR target. More specifically, we propose a DP model and use it to analyze the optimal stockpile acquisition strategies for China from 2008 to 2020, taking into account the impacts of different factors such as oil price, cost and risks.

The remainder of this paper is organized as follows. In Section 2, we propose a cost function-based DP model for analyzing China's oil reserve strategies. The implementation of the DP model is described in Section 3. Section 4 presents the main results and findings of our empirical analysis using the DP model. Section 5 concludes this study with some policy recommendations.

2. Methodology

2.1. Basic assumptions

DP is an effective technique for solving multi-period optimization problems, such as the evaluation of investment decisions for energy production expansion (Chorn and Shokhor, 2006; Kumbaroğlu et al., 2008) and the determination of optimal SPR (Chao and Mane, 1983; Teisberg, 1981; Zhang et al., 2009). In this study, we extend Teisberg (1981) and Zhang et al. (2009) and propose a DP model for deriving the optimal stockpiling path for China's SPR. Compared to Teisberg (1981) and Zhang et al. (2009), which assumed that all the oil stocks will be sold out in the end, in our DP model a certain oil reserve objective for the year 2020 needs to be satisfied based on China's SPR planning.

The establishment of the DP model requires two basic assumptions. First, the behaviors of China's oil storage have no effects on international oil prices. Second, the speculative behaviors of private stockpilers are not considered. According to Xue and Qiao (2009), currently China has an oil inventory of 300 million tons. It is estimated that the four SPR bases in China can be filled up by 2010 (Xue and Qiao, 2009). Under this scenario, China's average oil acquisition rate is less than 115 thousand barrels per day, which is approximately 0.1% of the global daily production of 85 million barrels. This small proportion is not likely to have major effects on international oil prices.[1] For the second assumption, Teisberg (1981) has shown that there would be no incentive for private stockpiling when the optimal level of the public stockpile is larger than the competitive equilibrium stockpile level. Furthermore, Murphy et al. (1989) pointed out that in most cases the combined inventory decisions made by public and private players are very close to the decisions made by only public players. Therefore, it is logic to assume that the speculative behavior of private stockpilers has no effects on China's SPR.

Our DP model also assumes that there are two basic states: (1) with oil acquisition behaviors, and (2) without oil acquisition behaviors in China's domestic oil market. A simple supply–demand model is used to determine the oil market prices for the two basic states. In the case of state (1), oil price is determined by the following equation:

$$S(p,i,t) = D(p,t) + u_t. \tag{1}$$

The solution to Eq. (1), which is referred to as the equilibrium price in this study, is a function of the acquisition amount u_t, the oil supply status i (normal or disruption) and time t, i.e. $p_t = P(u_t,i,t)$. For state (2), the base price, which is a function of the oil supply status i and time t, is determined by the following market-clearing condition:

$$S(p,i,t) = D(p,t). \tag{2}$$

2.2. DP model

The objective of the DP model is to minimize the total cost for attaining China's SPR target. The total cost function consists of three major components. The first is the loss of social welfare denoted by MC. It is convenient to measure China's consumer costs of establishing the SPR with respect to consumers' welfare during the basic market state without oil acquisition. Based on the price model in Section 2.1, we may determine the loss of social welfare as the loss of consumers' surplus under the consumption demand function for China:

$$MC = \int_{p_0(t)}^{P(u_t,i,t)} D(p,t)dp \tag{3}$$

where $p_0(t)$ denotes the base price. The second component is the purchase cost denoted by SC, which can be computed from the following equation:

$$SC = u_t * P(u_t,i,t). \tag{4}$$

The third component is the stockpile holding cost HC. By assessing an annualized unit holding cost v, the holding function can be expressed as

$$HC = v * (E(t) + u_t) \tag{5}$$

where $E(t)$ denotes the inventory size at the beginning of year t, and u_t is the acquisition size in year t.

[1] Considine (2006) showed that the gradual accumulation of strategic petroleum stockpiles has little impacts on oil prices, which provides further evidences on the reasonableness of the assumption.

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