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# Emission permit banking, pollution abatement and production–inventory control of the firm

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In this paper, we present a dynamic model modified with emission permit banking and pollution abatement, and investigate the effect of emission permit banking and pollution abatement on the production–inventory strategy of the firm. After introducing emission permit banking and pollution abatement, the cost function consists of the inventory holding and production costs, the cost of investment in abatement capital goods and the emission procurement/selling cost. Furthermore, the inventory holding costs are linear, production costs are non-decreasing and convex functions of the production level, and the costs of investment in abatement capital goods are increasing and convex functions of the investment level. We compare the optimal production–inventory strategy before emission permit banking and pollution abatement and thereafter. The mathematical investigation is based on the Arrow–Karlin model.



## 1. Introduction

The aim of this paper is to analyze the effects of emission permit banking and pollution abatement on the production–inventory strategy of the firm. Tradable emissions permits were conceived by Dales (1968), and were first instituted successfully in the US in 1976 as part of the Clean Air Act. Emission permits have since been used in the US for controlling air pollution, water pollution, acid rain control, ozone control, lead emissions, and most recently, in proposed legislation for greenhouse gas emissions. In an emission trading program, the regulatory authority issues a certain number of emission permits for firms, and each firm can legally emit only the level of emissions accounted for by the number of emission permits it holds. Firms can then buy and sell these emission permits with one another, creating a market for the emission permits. Firms can also reallocate these emission permits among different emissions sources within the firm itself.

The theoretical literature on tradable emission permits has established a number of important properties regarding the efficiency and optimality of their use (Cropper and Oates, 1992). One of the most important properties of tradable emission permits, established initially by Montgomery (1972), is that for any given emission standard, a system of tradable emission permits can achieve that standard at least abatement cost. As a consequence, tradable permits can improve social welfare relative to a standard since they achieve the same emission level, and therefore, the same damages at lowest cost. The efficiency gains arise because firms are allowed to move permits between sources so that firms equate marginal abatement control costs. Tradable permits have been much studied and researchers have considered numerous complications to the problem. A partial list includes the effect of market power (Hahn,1984; Godby, 2000), imperfect enforcement (Malik, 1992), regulated industries (Coggins and Smith, 1993), and optimality of incentive based systems relative to standards (Oates et al., 1989). Several papers have studied the market mechanisms underlying permits trading, addressing questions such as the impact of market power in the permits market, the role of initial permit allocations in market outcomes (Hahn, 1985; Misiolek and Elder, 1989; Eshel, 2005) or the consequences of allowing for permits banking in non-competitive tradable permits markets (Liski and Montero, 2005a, 2005b, 2005c, 2006).

Tradable emission permits may affect firms' production–inventory strategies. After introduction of the emission trading program, Dobos (2005, 2007) found the production–inventory costs will be higher, and the optimal production–inventory strategy will be smoother as well. Chaabane et al. (2012a, 2012b) presented a comprehensive methodology to address sustainable supply chain design problems where carbon emissions and total logistics costs, including suppliers and sub-contractors selection, technology acquisition and the choice of transportation modes, are considered in the design phase. Zhang and Xu (2013) investigated the multi-item production planning problem with carbon cap and trade mechanism, in which a firm uses a common capacity and carbon

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emission quota to produce multiple products for fulfilling independent stochastic demands, and the firm can buy or sell the right to emit carbon on a trading market of carbon emission. Furthermore, Li and Gu (2012) investigated the effect of tradable emission permits with banking on the production–inventory strategy of a firm.

The emission permit banking policy initiated successfully in 1986. Cronshaw and Brown Kruse (1999) designed experiments to study the features of the permit market initiated under the 1990 US Clean Air Act and found that subjects were able to achieve about two-thirds of the gains theoretically available from banking alone. Godby et al. (1997) and Mestelman et al. (1999) experiments also indicate that banking helps to smooth out the prices of permits. While some emissions trading programs allow unlimited banking, some do not allow any banking while others impose restrictions on the aggregate total of permits that can be banked.

Emission permit banking has played a large role in decreasing emission caps in the future. A salient example is the US Acid Rain Program, where banking has been a major form of emissions trading (Ellerman et al., 2000; Ellerman and Montero, 2002). The empirical findings also indicate that firms bank permits primarily as a hedge against uncertainty and for other firm-specific reasons (Considine and Larson, 2006). Cronshaw and Kruse (1991) took an important step in the tradable permits literature by developing a theoretical model of emission banking. The authors showed that the minimum cost to society and firms with banking is at least as low as the cost of a system without banking. Rubin (1996) provided a general treatment of emission trading, banking, and borrowing in an intertemporal, continuous-time model. Using optimal-control theory, the decentralized behavior of firms is shown to lead to the least-cost solution attainable under joint-cost minimization. Catherine and Rubin (1997) investigated firms' incentives for banking or borrowing emission permits and compares the emission and output streams firms would choose with the socially optimal solution. Rubin and Kling (1993) described trading behavior, attendant efficiency effects, and optimal design of intertemporal permit markets when pollution is certain. Contrary to prior work, Leiby and Rubin (1998) considered both stock and flow pollutants. In this literature, however, optimality can be achieved with either a sequence of single period emission permit markets in which the total number of permits issued each period is optimally chosen, or a suitably designed intertemporal permit trading program. A notable exception to this rule is a recent paper by Yates and Cronshaw (2001). The authors argue that intertemporal emission trading can sometimes be strictly superior to period-by-period permit markets when the government has imperfect information about aggregate abatement costs. In essence, when aggregate marginal abatement costs are high, intertemporal trading opportunities enable firms to mitigate these costs by borrowing emission permits from future periods; conversely, when aggregate marginal abatement costs are low, intertemporal trading enables firms to take advantage of attendant abatement economies by abating more pollution, and banking excess emission permits.

Emission permits are now widely considered as efficient instruments for regulating firms' emissions of pollutants. However, there is a concern that in the long run, a system of grandfathered permits may provide less incentive for firms to invest in abatement technologies or capital than a constant emissions tax, because the marginal abatement costs go down as firms invest, reducing the permit price and subsequently the benefits of investment (Milliman and Prince, 1989; Jung et al., 1996). Moreover, under tradable emission permits, the incentive to invest may be further reduced because permit prices are typically random and the investment is to a great extent irreversible (Xepapadeas, 1999; Chao and Wilson, 1993). In contrast, other policies such as standards or taxes do not introduce this additional uncertainty. The literature typically assumes exogenous and random permit price processes (Xepapadeas, 1999) or exogenous and random demand functions for permits (Chao and Wilson, 1993). In Baldursson et al. (1999), uncertainty is due to the entry and exit of polluting firms.

The option value theory of investment has led to a rich literature of empirical applications, also in environmental policy analysis. Herbelot (1992) used it to study utilities' choice of abating $SO_2$ emissions by installing scrubbers, substituting input or buying tradable emission permits. Insley (2003) also studied the choice faced by U.S. power plants to install scrubbers to control sulfur emissions, assuming that $SO_2$ permit prices are stochastic and explicitly accounting for the long construction process. Hassett and Metcalf (1993, 1995a, 1995b) analyzed residential energy conservation investments assuming that energy prices follow a Brownian motion. The resulting hurdle rate for energy conservation investment is about four times higher than the standard hurdle rate when there is no uncertainty. Purvis et al. (1995) studied the adoption of free-stall dairy housing with stochastic milk production and feed costs, and found a hurdle rate around. Diederen et al. (2003) studied the adoption of energy saving technologies in Dutch greenhouse horticulture with uncertainty in the energy price and the energy tax and found a hurdle rate of almost twice the rate predicted by net present value calculations. Khanna et al. (2000) analyzed the adoption of site-specific crop management with stochastic output price and expectations of declining fixed costs of the equipment. Carey and Zilberman (2002) simulated the adoption of irrigation technology when water price and supply are stochastic. Lin et al. (2007) extended the basic model of option value in environmental economics studying the optimal timing for adopting pollution prevention policies for the greenhouse effects. Further, the recent papers by Ansar and Spark (2009) and Lin and Huang (2010, 2011) refined the previous contributions aiming at explaining the so called energy paradox, that is the reluctance of firms to make energy-saving investment (Hausmann, 1979; Hassett and Metcalf, 1993, 1999; Jaffe and Stavins, 1994).

Following the framework of Dobos (2005, 2007), we present a dynamic model modified with emission permit banking and pollution abatement, and investigate the effect of emission permit banking and pollution abatement on the production–inventory strategy of the firm. We examine the convex cost model of Arrow and Karlin (1958). The convexity of the cost model was experienced in the empirical analysis (Ghali, 2003). The firm is able to purchase additional emission permits or to sell from its emission permits after the introduction of emission trading, and can bank unused emission permits for use in a future period. The reallocation of emission permits will change the cost of the firm, and may affect the firm′s production–inventory strategy. We will mainly investigate such effect in this paper. The results of this study complement and extend the work of Dobos (2005, 2007) by providing a dynamic model modified with emission permit banking and pollution abatement.

The paper is organized as follows. In Section 2 three models will be shown to be compared: the basic Arrow–Karlin model, the model with tradable permits which was given by Dobos (2005, 2007) and the model modified with emission permit banking and pollution abatement. In Section 3 we will show that emission permit banking and pollution abatement smoothe the production level of the firm and the inventory level will be higher. In Section 4 we describe some properties of an optimal solution compared to the basic model. In Section 5 we illustrate the results of the paper with a numerical example. In the last section we will summarize the results of the paper.