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THEORETICAL ARTICLE

A hybrid carbon policy inventory model with emission source-based green investments

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Abstract
The present study analyzes a production-inventory system with hybrid carbon regulation policy. This hybrid carbon policy is a combination of carbon tax and cap-and-trade policies. It considers a single item that can be produced in different qualities. Production cost, setup cost, amount of emissions and the demand rate depend on the quality. The demand rate for each quality is price sensitive. Emissions occur from three sources—setup, production process and stock holding. The firm can invest on green technologies in each emission source separately to reduce emissions. This model considers profit maximization policy. The managerial problem is to select the profit-maximizing quality for production, and to find the optimum values of the production run time, green investments and the selling price. An algorithm is provided to solve the model. The model is illustrated by a numerical example. Sensitivity analysis is also performed.

Keywords Cap-and-trade · Carbon tax · Emission · Green investment · Inventory · Production

1 Introduction

Catastrophic effects of global warming are well-known to us. In a special report published in 2018, the Intergovernmental Panel on Climate Change (IPCC) mentioned that a number of climate change impacts that could be avoided by limiting global warming to 1.5 °C, compared to 2 °C or more. For instance, by 2100, the rise of global sea level for 1.5 °C global warming would be 10 cm lower compared to 2 °C global warming (https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report (Accessed on 05 June 2019)). Tollefson [31] mentioned,

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"Two degrees of warming could destroy ecosystems on around 13% of the world's land area, increasing the risk of extinction for many insects, plants and animals. Holding warming to 1.5 °C would reduce that risk by half". Human activities, like industrialization, urbanization etc. are main causes for global warming. It has been observed by the scientists that the carbon emissions play major role in global warming because of its heat trapping property. Industry sector is one of the major carbon emitters. In a report, published in 2014, the US Environmental Protection Agency (EPA) noted that industry was the third major contributor to GHG emissions contributing 21% of the total GHG emissions in US. A country's economic growth largely depends on its industrial growth. So, no country will shut down its industries to reduce emissions. Instead, the government of a country should adopt strong emission regulation policies. Many countries are implementing carbon emission regulation policies to compel the emitters taking serious actions to reduce emissions. Carbon tax and cap-and-trade are two well-known polices adopted by many countries. Under these carbon policies, a firm needs to reset the optimal values of the decision variables [8]. To reduce the burden of carbon tax, an industrial firm can considerably reduce emissions by investing on green technology in production process, warehouse, transportation [4, 23].

In recent times, there is a growing interest among the researchers to investigate sustainable inventory models and supply chain under various realistic situations. Hovelaque and Bironneau [19] discussed a carbon-constrained EOQ model with price and emission sensitive demand. Aliabadi et al. [1] analyzed an inventory system of deteriorating items with carbon emission and credit period sensitive demand. Many research publications are available in inventory and supply chain literatures which consider sustainability as one of the prime factors (e.g. [2, 3, 6, 7, 9, 12, 14, 15, 17, 18, 20–22, 27, 28, 33]. None of these studies considers green investment as a decision parameter. There are three main sources of emissions in a production-inventory system. These sources are—setup, production process and stock holding [3, 12, 27]. Emissions can be reduced considerably in each of these sources by investing on green technologies and green systems. Toptal et al. [32] incorporated green investment as a decision parameter in a retailer's decision model under different emission regulations. Lou et al. [24] considered green technology investment as one of the model parameters in a supply chain model with emission trading policy. In a study, Bi et al. [5] discussed on governmental subsidy policy to motivate firms' adoption of green investment for environmentally discerning consumers. A system with defective product under carbon tax and green investment was investigated by Datta [12]. None of these articles considers emission source-based green investment. Further, all the studies mentioned above discuss different carbon policies separately. Both policies, carbon tax and cap-and-trade, have advantages and disadvantages. In the existing literature, many research articles are available which compare these two policies (e.g. [13, 16]). To overcome the disadvantages of these policies, some authors proposed a hybrid mechanism by mixing these two policies. Mandell [26] investigated a situation where one part of the economy is controlled by cap-and-trade mechanism and the rest by carbon tax. Snyder [29] proposed a hybrid system where emission companies pay tax at a fixed rate and the government uses the carbon tax to buy the companies' emissions credits in the carbon market. Sun

and Kuang [30] simulated the effects of a hybrid policy on the economy in a CGE (Computable General Equilibrium) model. Zhang et al. [34] proposed a hybrid carbon policy consisting of a combination of progressive carbon tax and carbon trading policy. They discussed about how it could be implemented in small and large enterprises. None of these papers shows the effects of this proposed hybrid carbon policy

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One critical observation is that none of the studies available in inventory literature focuses on emission source-based green investment. Emission source-based green investment is more practical because fund allocations in these sources are important decision variables, particularly when green budget is fixed. Another observation is that none of the researchers incorporates hybrid emission regulation policy in a production-inventory model. These observations provide the motivation of the current work, in which we investigate a firm's production-inventory system with hybrid carbon policy and emission source-based green investment. This is the first attempt to use source-based green investment in a model. The demand rate is considered as price sensitive. The firm has to select only one quality for production from a multiple quality options that maximizes its average annual profit. The contributions of this study with respect to the studies available in existing literature are threefold. First, it incorporates hybrid carbon policy in a production inventory system. Second, the green technology investments are emission source-based and independent. Third, the selection of profit-maximizing quality for production from multiple-quality options is a decision parameter. To the best of the authors' knowledge, the current study is the first study which considers hybrid carbon policy, multiple-quality and source-based green investments in a system for analysis.

The rest of this paper is organized as follows. Section 2 describes the assumptions and notations used in the model. The model development is presented in Sect. 3. Solution of the model and the solution algorithm are presented in Sect. 4. Numerical example and sensitivity analysis are provided in Sects. 5 and 6 respectively. Section 7 derives the condition for simultaneously optimizing average profit and average emission. Section 8 provides some concluding remarks.

2 Assumptions and notations

Following are the assumptions and notations used to develop the proposed model.

Assumptions:

(a) Time horizon is infinite.
(b) The firm can produce the item in n different qualities. However, the firm decides to produce only one of these qualities that maximizes its average annual profit.

Model parameters are different for n different qualities. All qualities are marketable, but demand rates are different.
(c) Demand rate is price sensitive.
(d) Production rate is constant.
(e) Three sources of carbon emission are—set up (source 1), production process (source 2) and holding the produced items (source 3) (as in Arslan and Turkay [3], Marti et al. [27] and Datta [12]).
(f) The firm has the opportunity to invest on green technology in each source of emissions separately to reduce emissions.
(g) We use a hybrid carbon policy in this model. This policy is a combination of carbon tax and cap and trade policies. In this policy, the firm receives free annual