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How to upgrade an enterprise's low-carbon technologies under a carbon tax: The trade-off between tax and upgrade fee ☆

Senyu He [a,b,c], Jianhua Yin [d], Bin Zhang [a,b,c,e], Zhaohua Wang [a,b,c,e,*]

[a] School of Management and Economics, Beijing Institute of Technology, 100081 Beijing, China
[b] Centre for Energy & Environmental Policy Research, Beijing Institute of Technology, 100081 Beijing, China
[c] Collaborative Innovation Centre of Electric Vehicles in Beijing, 100081 Beijing, China
[d] Business School, University of International Business and Economics, 100029 Beijing, China
[e] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing100081, China

HIGHLIGHTS

- Proposed a new method to balance carbon tax and technology upgrade cost.
- Optimised the enterprise's technology upgrade strategy under carbon tax.
- Tax rate is more sensitive to enterprise with a stricter control on expected cost.
- Low tax rate hardly promotes enterprise with a loose control to reduce emission.
- Excessive carbon tax makes enterprise give up its technology upgrade plan.

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ABSTRACT

Reducing CO_2 emissions is a hot topic, and an important policy to achieve this target is carbon tax. When an enterprise is subject to a carbon tax, it has to pay this extra fee for the long-term if it does not upgrade its production technology. It needs to pay a certain upgrade fee in the short-term if it chooses to upgrade its plant. Thus, it has been an important problem for enterprises seeking to balance the trade-off between the 'long-term tax fee' and the 'short-term upgrade fee'. This paper explores how to optimise an enterprise's production technology upgrade strategy based on existing low-carbon technologies, to minimise the total upgrade cost subject to an expected total cost per product. An integer programming model is proposed to formulate the problem, and a 'multi-agent system – genetic algorithm' method is presented for its solution. The model is applied to a numerical example and the results indicate that the proposed method is feasible. The impacts of carbon tax and enterprise's expected cost on its technology upgrade strategy are further discussed.

1. Introduction

Excessive CO_2 emissions are one of the main causes of global warming. To cope with global warming, the world reached a consensus for reducing CO_2 emissions through a series of negotiations. Some countries adopt a carbon tax policy to achieve target reductions, such as: Denmark, Finland [1], Canada [2], etc. Many scholars have discussed the impact of a carbon tax from the country or regional perspective [3–7], but few of them research this from the perspective of enterprise. Some scholars propose that a carbon tax exerts a somewhat negative influence on enterprise. For example, Al-Amin et al. [8] state that overly strong carbon tax policies reduce an enterprise's savings and investments. Jie et al. [9] think that implementation of carbon tax policies reduces the 'living space' of small- and medium-sized enterprises.

When an enterprise is subjected to a carbon tax, it will see an increase in extra tax costs, which drives total cost increases. If it does not reduce its carbon emissions, it has to pay this extra cost for the long-term, which is not conducive to its development [10]. Therefore, the carbon tax will urge an enterprise to upgrade its current production technologies to low carbon ones to reduce carbon emissions [11]. In this paper, "low carbon technologies"

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* Corresponding author at: School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China.
E-mail address: wangzhaohua@bit.edu.cn (Z. Wang).

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Nomenclature

$CE_{i,j}$	the cumulative carbon emissions when accumulating to phase i process j
$CPC_{i,j}$	the cumulative production cost when accumulating to phase i process j
$CUC_{i,j}$	the cumulative upgrade cost when accumulating to phase i process j
$e_{i,j,m}$	the mth technology's carbon emissions per product in phase i process j
$I_{i,j,m}$	indicator function, $I_{i,j,m} = 0$ indicates the mth technology is not selected in process $P_{i,j}$, and $I_{i,j,m} = 1$ means the mth technology is selected
$input_{i,j}$	the collection of phase i process j's previous production processes
$LUC_{i,j}$	upper bound on the $CUC_{i,j}$ when accumulating to phase i process j
$P_{i,j}$	the jth production process of phase i
$pc_{i,j,m}$	the mth technology's production cost per product in phase i process j
r	carbon tax rate
$T_{i,j,m}$	the mth potential technological options for phase i process j
TE	per product carbon emissions
TPC	per product total production cost
TPC_0	per product total production cost when the carbon tax is not levied
TUC	the enterprise's total upgrade cost
$uc_{i,j,m}$	the mth technology's upgrade cost in phase i process j
α	expected cost change rate

refer to technologies which emit less carbon dioxide per product in production than current technologies. On the other hand, the enterprise has to invest a lot of extra capitals in the short-term when it chooses to upgrade. It has been an important problem for enterprises when considering how to balance the trade-off between the 'long-term tax fee' and the 'short-term upgrade fee'.

Enterprise's production networks have become more complicated, and involve more production processes. If upgrading all production processes to a more advanced technology, major cost pressures accrue with significant emissions reduction. As the enterprise is essentially benefit-oriented, this does not conform to its pursuit of interest. It will choose some appropriate production processes for which to upgrade the low carbon technology, which render both carbon emission reduction and upgrade costs acceptable. In addition, there may be a number of possible technologies applicable to each production process. The production cost, carbon emissions, and upgrade costs may also vary. These factors cause an enterprise to face many choices [12]. How to choose appropriate production processes and upgrade them to the appropriate technological status has become the key for an enterprise to complete technology upgrades under a carbon tax policy in a successful fashion.

Recently, several studies have been concerned with enterprise investment strategies for low carbon technologies under the carbon tax policy. Some studies focus on investment response [13–16]. For example, Baker et al. [13] determined a firm's profit maximising research and development (R & D) investment response under to an uncertain carbon tax. Zhou et al. [16] proposed that the carbon tax policy sends the strongest investment signal. Furthermore, some research plays attention to investment choice [12,17,18]. Gharaie et al. [12] evaluated the trade-offs between the cost of emissions reduction options and the effect on overall CO_2 emissions, and used a hierarchical conceptual design procedure to find the most appropriate strategy for CO_2 emissions reduction. Thoma [17] obtained that a carbon tax will change respective profitability rankings of different technologies. These problems are essentially combinatorial problems, which are usually formulated by an integer programming model [19–23]. Thus, this paper also uses integer programming model to describe problems.

In theory, all integer programming models can be solved by enumeration. However, considering the calculation time and the size of such models, they are often solved by use of an intelligent algorithm, such as genetic algorithm, ant colony optimisation. Here, a method based on multi-agent system (MAS) combined with genetic algorithm (GA) is used. The MAS is a form of distributed artificial intelligence. It enables a whole problem to be decomposed into several interacting local problems [24]. Each agent has a certain level of autonomy, and uses its resources to solve one of these local problems. Agents are able to communicate with each other, and achieve the final goal through collaboration or competition [25]. Thus, the whole problem can be solved much faster. The MAS is commonly used to obtain a decentralised solutions where a central, controlled, solution method is not applicable [26], such as in energy management systems [27,28], smart grid systems [29,30], and so on.

In the previous studies, the low carbon technologies are mainly based on research and development (R & D) [12–18], which proved useful for the long-term development of an enterprise. However, the new technology may fail and the journey from theory to practice is often long. During the R & D period, enterprises have to use existing low-carbon technologies to solve cost problems caused by the carbon tax. Nevertheless, the literature concerning optimisation based on existing low-carbon technologies is sparse. To fill this research gap, an integer programming model is proposed to optimise enterprise's technology upgrade strategies by using existing low-carbon technologies under a carbon tax policy in this paper. Suppose that the existing product's production network structure, details of various optional potential low-carbon technologies, and the per product expected total cost are available, the model proposed in this paper attempts to address the following problems: (1) Which production processes need to be upgraded? (2) Which existing low-carbon technology should be selected? (3) What is the lowest total cost for these technology upgrades?

The rest of this paper is organised as follows: in Section 2, an integer programming model is proposed for the problem and a 'multi-agent system–genetic algorithm' (MAS-GA) method is presented to solve this model; the model is applied to a numerical example and solved by the MAS-GA method in Section 3; in Section 4, the impacts of carbon tax and enterprise's expected cost on the its technology upgrade strategy are further discussed; conclusions are drawn in Section 5.

2. Methodology

2.1. Problem representation

A typical production activity consists of several production phases, such as procurement and processing of materials, parts production, assembly, packaging, transportation, storage, and so on. Each phase contains a number of production processes, in which the detailed production is undertaken, such as the

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