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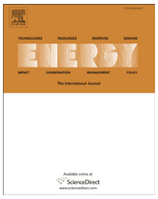

An assessment of the energy-saving potential in China's petroleum refining industry from a technical perspective

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ABSTRACT

As a major contributor to productivity and employment in China, the petroleum refining industry consumes approximately 15% of industrial fuel oil and 10% of industrial coal. Given this energy-intensive characteristic, cost-effective investments for energy-efficient technologies may be a useful strategy to improve the competitiveness of China's refining industry. More importantly, this approach may alleviate the environmental problems China faces. This paper addresses the challenges posed by a highly complex refining system, incomplete industrial information, and the absence of a widely accepted evaluation method. This study models and analyzes the energy-savings potential for refining and conversion processes in the context of technological change. The results indicate that upgrading process heaters have been a priority during recent years, but heat recovery and advanced process control systems will gradually begin to dominate the technological marketplace in the long term. Current technology policies will result in approximately 2.7×10^8 GJ of energy savings by 2020, keeping the average energy consumption of refineries within 57 kg oil equivalent (kgoe)/t-feed. If a cap-and-trade scheme is introduced in the future, a further reduction of up to 10% can be achieved. Various specific barriers that impede the realization of potential goals are also addressed in this study.

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1. Introduction

The petroleum refining industry in China is the second largest such industry in the world and provides products to many other sectors, including the transportation and chemicals industries. As of January 2010, China's petroleum refining industry operated 54 refineries and yielded profits in excess of 1800 billion RMB (Renminbi, Chinese Yuan) in 2009 [1,2]. China's petroleum refineries must expand to accommodate growing urbanization and the concomitant rise in transportation demand. Sixty percent of a refinery's operating costs are typically spent on energy. Enhanced energy efficiency helps refineries reduce costs as well as environmental pollution and greenhouse gas emissions.

The petroleum refining industry consumes approximately 15% of industrial fuel oil and 10% of industrial coal [3]. Energy use in refineries fluctuates due to changes in the types of crude that are processed, the product mix and complexity of the refinery, and the sulfur content in the final products [4]. In 2010, the energy consumption of refineries was equivalent to approximately 30 million tons of oil, which is approximately 1.5 times more than the energy consumption ten years ago and twice as much as fifteen years ago [5,6]. Energy consumption will continue to increase because of trends toward more complex processing systems with better conversion capacities. China's government has implemented policies to facilitate energy management practices in petroleum refineries [7–9]. Over the past decade, the CNPC (China National Petroleum Company)and SINOPEC (China Petroleum and Chemical Corporation) have decreased their unit energy consumption by 28% and 34%, respectively [2,5]. Nevertheless, their energy consumption is still 13% higher than that of U.S. refineries (53 kgoe/t-feed), indicating significant room for improvement in energy consumption [10,11]. It is necessary to clarify the potential for improvement with regard to the effectiveness and cost of available technology to implement policies and attract relevant investment.

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In addition, the use of energy-efficient technology will also meet the challenges posed by modern refineries that consist of more complex and integrated systems. Historically, Chinese refineries were only capable of distillation and lacked reforming or converting capacities in accordance with domestic low-sulfur crude. The adoption of energy-efficient technologies only addressed problems with distillation heaters and the control of the reflux ratio. In the early 1990s, China became a net importer of high-sulfur crude oil and began taking steps to modernize refining systems that not only distill hydrocarbon compounds but also convert and blend them into a wider array of products [4,12]. Today, technological opportunities are no longer limited to distillation but have expanded to oil upgrading, conversion, treating, and blending as well as systems for the optimal control of an integrated refinery [13].

The United States and Brazil have implemented research programs to use comparative benchmark data to quantify technological opportunities in energy efficiency improvements of petroleum refineries [4,14–17]. Their results showed the potential improvements that could be realized if refineries adopted all available commercial energy-efficient technologies over the next decade. The potential benefits were most likely overestimated when investment returns, market competition, and policy restriction were not considered. Johansson et al. investigated European petroleum refineries that could save 0.17 GJ (GJ) per year by using short-term mitigation options, such as fuel substitution and energy efficiency measures [18]. The estimated energy-saving potential for the individual abatement strategies depended on strong assumptions made in the analysis. The results were subject to considerable uncertainty with respect to the choice of technology and scope of implementation. Park et al. created a system dynamics model that incorporated a basic energy/raw material flow and process flow to evaluate the energy saving potential of the petroleum refining industry in Korea [19]. This model focused on the change in production capacity but ignored the impact of cost-effectiveness on technology adoption. Existing bottom-up energy demand models (e.g., MARKAL, DNE21+, AIM/end-use and PRIMES) explicitly consider the stock turnover based on a single objective cost criterion and are well-suited to identify promising technology options in complex systems at the regional level. However, these models have, to the best of our knowledge, not been applied to analyses of potential energy savings in the Chinese petroleum refining industry.

Based on the current body of literature, we attempted to develop an optimization model that accounts for the factors that affect technology adoption. To do so, we combined a bottom-up approach with technology diffusion theory to predict how technology will be implemented in the future and to assess potential energy savings. A bottom-up approach was used to establish the relationship between technology adoption, energy savings, costs, production plans, and policy constraints. Previous research on technology selection in other industrial sectors (e.g., lime, pulp and paper) has proven the applicability of this approach [20–23]. In contrast to previous research, this study contributes an industrial bottom-up energy efficiency model based on the following aspects: 1) detailed real-life technological parameters from Chinese refineries and industrial data of the entire sector's composition as of 2010; 2) explicit application of energy-efficient technologies in Chinese refineries. These applications are convenient for the users to consider the future role of energy efficiency improvements in the overall Chinese energy strategy; 3) a detailed introduction of the carbon policy instrumented under China's cap-and-trade scheme. This introduction reflects the decision-making criteria and quantifies the impacts of the emission cap and price on pathway selection in the Chinese petroleum refining industry.

This paper is organized as follows: Section 2 presents the overall structure of the optimization model and the acquisition of input parameters. A cap-and-trade policy scenario is introduced into this model, which helps to quantify the impacts of the carbon cap and price on pathway selection in the Chinese petroleum refining industry. Section 3 predicts the technology diffusion trends for six principle refining processes, analyzes their potential energy savings, and simulates the uncertainties using the Monte Carlo technique. It also presents how this potential changes under future cap-and-trade schemes and carbon emission reductions that result from improved energy efficiency. Section 4 concludes with implications of this model for the design of economically feasible and environmentally friendly technology regulations.

2. Methodology

2.1. An overview of the model

To build a model that combines a bottom-up approach with technology diffusion theory, we begin by selecting principle refining processes and the practical technologies that are applicable to the six processes as the crucial parts of the entire system. The model is designed to optimize the cost-benefit ratio of the refining process and prioritize technologies that will help refineries meet energy conservation objectives while accounting for capacity and technology adoption constraints. The model is presented in Fig. 1. We subsequently describe the classification and acquisition of the model's input parameters.

(1) Bottom-up module: Based on the bottom-up modeling approach, this module performs a structural analysis of the refining process, selects key energy-efficient technologies, and matches energy-efficient technologies with refining processes based on the operation flowchart.

(2) Optimization module: For each refining process, dynamic technological structures can be modeled as optimal solutions by maximizing the ratio of annual energy savings to technological costs that meet national energy conservation objectives. The expected result is determined by two categories of variables. The first category of variables is introduced capacity ($x_{n,t}$), which drives increases in the annual installation capacity. The other variable category is the technology diffusion coefficient ($\alpha_{n,i,t}$, $\beta_{n,i,t}$), which describes the diffusion of technological information through two channels: 1) autonomous acquisition, where potential adopters take the initiative to use new technologies and 2) influence by previous technology adopters. The probability of autonomous acquisition, α, is referred to as the external effect coefficient. The probability of influence by previous adopters, β, is referred to as the internal effect coefficient.

(3) Input module: Two types of parameters are required to support the model's operation. Sectoral parameters are used to predict changes in the installation capacity over the next decade (constraint 1). Energy conservation requirements (constraint 2) and financial measures of energy savings (objective) are also quantified. Technological economic parameters apply to the measurement of energy savings, investment costs, and market share for each specific technology that are necessary for the model's objective and all the constraints.

(4) Output: The direct output of the model simulates technology diffusion trends for six principle refining processes to calculate potential energy savings. A Monte Carlo simulation was used to study the output distribution of optimal solutions and evaluate changes in potential energy savings for the petroleum refining industry.

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