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Eco-efficiency assessment of coal-fired combined heat and power plants in Chinese eco-industrial parks

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ABSTRACT

This study applied a slacks-based data envelopment analysis (DEA) model to assess the eco-efficiencies of 44 coal-fired combined heat and power (CHP) plants (with 160 units) in 31 Chinese eco-industrial parks. The inputs of the DEA model include coal consumption, freshwater consumption, capital depreciation, and operating cost. The outputs are electricity, heat, and GHG emission. The key findings are that the eco-efficiencies of the CHP plants considered are quite different from thermal energy efficiencies, and annual working time is the most important factor affecting eco-efficiency positively. It is indicated by sensitivity analysis that consideration of freshwater consumption and capital depreciation will have a significant impact on eco-efficiency. The results also present that the CHP plants with a capacity less than 120 MW are generally more scale-effective. The role of featured industries in the host park was explored by a hierarchical clustering method, and we found that the more energy-intensive industries the parks host, the lower CHP eco-efficiencies they will have. Based on the findings, policy implications were proposed for improving CHP eco-efficiency in industrial parks, including enhancing utilization level, retrofitting turbine technology, and increasing heat-to-electric ratio of in-use CHP stocks, and controlling the plant-level capacity of new CHP projects.

1. Introduction

Early in 2000, the concept of carbon lock-in was proposed by declaring that ‘industrial economies have been locked into fossil fuel-based energy systems’ because of the dependence of their initial development path and institutions (Unruh, 2000). Transforming the carbon-intensive mode of industrial development in a short period poses a great challenge because of its enormous replacement cost (Unruh, 2002). Reducing the carbon intensity of energy infrastructure and increasing water-use efficiency has been highlighted in Sustainable Development Goals proposed by United Nations (UN, 2016). Assessing and improving the environmental performance of energy systems will pave a solid way to facilitate low-carbon development. Facing with the challenges of global climate change and water scarcity, China has attached great importance to mitigating greenhouse gas (GHG) emission and water conservation (CSC, 2015; Sun and Liu, 2016). The large numbers of industrial parks have been playing a dominant role in industrial development of China (MIIT, 2011). Shareable energy infrastructure is a common practice in industrial parks and is also a key node in the material-energy metabolism systems of industrial parks (Lu et al., 2015) that links energy use, water use, and solid waste, such as the case of the Kalundborg symbiotic system (Chertow and Ehrenfeld, 2012) and many eco-industrial parks documented in literature. By the end of 2016, there are more than one hundred industrial parks listed in the China's national eco-industrial park program, which is initiated by the Chinese Government in 2000 (Tian et al., 2014; Guo et al., 2017).

In a previous study (Guo et al., 2017), it was shown that energy infrastructure, mainly in the form of combined heat and power (CHP), generally accounts for a large share of GHG emissions in the Chinese eco-industrial parks and the energy infrastructure has a high level of coal-dependency. Besides, a large body of literature has explored the close linkage between energy production and

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water consumption associated with energy infrastructure, also called the energy-water nexus (Perrone et al., 2011). In 2014, CHP accounted for 30.8% of total capacity of thermal power plants in China (CEC, 2014). The efficiency of a CHP plant is sensitive to many factors, such as the capacity, technology, annual working time, and ratio of heat to electricity. This study aims to assess the eco-efficiencies of coal-fired CHP plants in Chinese eco-industrial parks, by comprehensively considering multiple inputs and outputs, and then try to identify the key factors which impact the CHP eco-efficiencies from the perspective of facility level and park level.

In light of the popularity of CHP implementation and the importance of CHP to improve energy efficiency, there is a large body of literature on such topic. Thermal conversion efficiency (calorific value ratio of secondary energy output to primary energy input) and GHG emission per unit of electricity generated (e.g., ton CO_2 e/MWh) has been broadly used to assess the performance of CHP (EPA, 2015; Hertwich et al., 2014). However, they are unilateral indicators that do not consider some other crucial inputs, such as freshwater consumption, capital investment and operating cost. In particular, CHP plants consumed freshwater not only for cooling like electricity-only power plants, but also for heat supply. The outputs of CHP plants include electricity and heat. Thus it is necessary to consider multiple inputs and outputs of CHP plants simultaneously and without preference to some factors in the assessment of comprehensive efficiencies. The methodology of data envelopment analysis (DEA) is appropriate for such problem of assessing the relative efficiencies of comparable entities (Farrell, 1957), i.e., decision-making units, without prior assumptions regarding the underlying functional relationships between inputs and outputs (Seiford and Thrall, 1990). DEA has been intensively applied to evaluate the performances of different types of entities engaged in a number of contexts (Cooper et al., 2010), such as in energy and environmental studies (Zhou et al., 2008). E.g., the environmental performance of electricity generation and regional industry in China were assessed by employing DEA (Zhou et al 2012; Chen and Jia, 2017). Especially, a DEA approach combined with sequential Malmquist index was employed to evaluate the dynamic environmental performance of Chinese eco-industrial parks (Liu et al., 2015). DEA has also been used in the performance assessment of coal-fired power utilities, both at the plant and unit levels. Sueyoshi et al. (2013) applied a method of DEA window analysis to capture a frontier shift of coal-fired power plants in the U.S. between different periods, which indicated technology progress on desirable and undesirable outputs. Yang and Pollitt (2010) emphasized the necessity of properly distinguishing the disposability features among undesirable outputs, which was illustrated in a DEA-based study of 582 Chinese coal-fired power plants in 2002. Song et al. (2015) analyzed the energy efficiencies of 34 coal-fired power units in China using an input-oriented model of DEA and identified that the energy efficiencies would be much sensitive to two key factors, the load factor and cooling method. In the studies mentioned above on coal-fired power utilities, the inputs considered in DEA involve fuel consumption, number of employees, freshwater consumption, auxiliary electricity consumption, establishment cost of plant (or installed capacity), and operating cost, while the outputs include net electricity generation, capacity utilization, SO_2, NO_x, and CO_2.

However, there are still some gaps on assessing the comprehensive efficiency of CHP plants in Chinese industrial parks while employing the DEA methodology, such as considering different categories of secondary outputs and the impact of the industrial structure of industrial parks, besides regular factors like fuel inputs, GHG emissions, freshwater consumption, and costs of construction and operation simultaneously. In this study, we aim to enrich the application of DEA to assess the eco-efficiencies of CHP plants in Chinese eco-industrial parks and then identify the underlying factors both at the facility level and the park level. The assessment model is developed on the basis of a slack-based measure of DEA. The results will provide a decision-making foundation for low-carbon and water-saving shifting of in-use CHP stocks and future planning for new CHP projects.

2. Materials and methods

2.1. Data collection and description

Coal-fired CHP utilities are defined as the objective in this study. A CHP plant mostly has several units, and a CHP unit generally consists of several boilers and a turbine (EPA, 2015). Based on a first-hand investigation, the inventory of 44 coal-fired CHP plants including 160 units in 31 Chinese eco-industrial parks was established. The spatial distribution of the eco-industrial parks and their CHP plants are presented in Fig. 1. The coal-fired CHP units considered in this study are located in eight provinces of China, mostly in the coastal area of East China. The individual capacities of CHP units fall in the scope of [3 MW, 300 MW]. The number of CHP units in each park ranges from 1 to 18, and the total capacity varies from 12 MW to 2,254 MW. The information as follows are carefully checked: (1) plant-level information, such as fuel inputs, annual working hours, and secondary energy outputs; (2) unit-level information, such as capacities, turbine technologies, and cooling technologies; and (3) park-level information, including energy consumption, industrial added value, leading industries. Most of the data is in 2012 and the detailed information can be found in Appendix A.

2.2. Modeling eco-efficiency of CHP plants with a slacks-based measure of DEA

A slacks-based DEA model is applied to assess the eco-efficiency of CHP plants (Fig. 2). The decision-making unit is a CHP plant. The inputs include coal consumption, freshwater consumption, capital depreciation, and operating cost (excluding fuel and water costs). The outputs include electricity, heat, and GHG emissions. The first two outputs are defined as desirable outputs, while the last output is defined as undesirable one. In this study, SO_2 and NO_x emissions are not included in the outputs as usual practice in previous DEA studies on similar topic. One of the main reasons is that, after the mandatory ultra-clean retrofitting implementation (MEP, 2015), nearly all of the CHP plants considered will achieve very low SO_2 and NO_x concentration in the off-gas without substantial difference.

The freshwater consumed in CHP plants works for cooling, heat supply (mainly in the form of steam or hot water), boiler water makeup, slag removal, and flue gas desulfurization (Hong, 2006; Zhang et al., 2016). The water used for cooling is much more than the other processes mentioned above (excluding heat supply) (Fthenakis and Kim, 2010; Macknick et al., 2012). Small part of the electricity generated is self-consumed and the most part is uploaded to the regional power grid. The heat is supplied to the plants in the host industrial park.

Based on the slacks-based DEA model, the eco-efficiencies of CHP plants can be assessed as follows.

2.2.1. Inputs and outputs

The parameters and variables used in the model are defined in Table 1. The values of the parameters are listed in Table S1 in the Appendix B.

The turbine technologies employed in CHP units can be summarized as extraction-condensing technology (EC) or back pressure