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Research article

Stochastic optimization of hybrid electricity supply chain considering carbon emission schemes

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ABSTRACT

This paper focuses on designing an optimal hybrid electricity supply chain (HESC) that considers carbon emission schemes and uncertainties. Both coal and biomass are used as fuel for electricity generation. Several carbon emission schemes, such as carbon cap and trade, carbon cap, and carbon tax, are considered. In addition, uncertainties such as coal mining rate, biomass yield rate, and electricity conversion rate are considered while designing HESC. A stochastic mixed integer linear programming (SMILP) model is developed that aims to determine optimal HESC under carbon emission schemes and uncertainties. A case study of North Dakota (ND) in the United States (US) is used to demonstrate the effectiveness of the proposed model. The results suggest that carbon emission schemes significantly impact the HESC design. Sensitivity analysis is further conducted to provide managerial insights.

1. Introduction

During the past several decades, coal has been used as a primary source of energy to generate electricity. However, coal is nonrenewable and has been the source of energy security concerns. In addition, the use of coal for electricity generation has resulted in a significant increase in greenhouse gas (GHG) emissions. Therefore, it is necessary to look for alternative coal substitutes, which should be both renewable and environmentally friendly. One such potential replacement which fulfills those requirements is biomass, increasingly viewed as an alternative in recent years. There are several edible and non-edible biomasses. However, lignocellulosic biomass – such as switchgrass, miscanthus, agricultural residues and woody materials – are preferred for electricity generation because they are non-edible (Akgul et al., 2012). These biomasses are perennial and absorb GHGs from the atmosphere during the growth process (Cuellar, 2012). Since the electricity generation from coal is widely in use and biomass-based electricity generation provides both energy security and environmental benefits, designing a hybrid electricity supply chain (HESC) in which both coal- and biomass-based electricity generation are simultaneously considered will enable to gradually fulfill the future sustainability goals.

In recent years, the increase in environmental concerns has forced government agencies to develop and adopt various carbon emission schemes such as carbon cap and trade, carbon cap, and carbon tax. A carbon cap and trade scheme (CCTS) is a policy in which the government sets a carbon quota for companies and allows the companies to trade carbon emissions across different agencies, if their carbon emissions are above or below the carbon quota (Jin et al., 2014). A carbon cap scheme (CCS) is an inflexible carbon quota policy in which the government puts hard carbon quota (cap) on the companies (Jin et al., 2014). A carbon tax scheme (CTS) is a policy in which the government taxes the companies for emitting carbon irrespective of the amount of carbon emitted (Jin et al., 2014). While these carbon emission schemes uses different mechanisms to reduce carbon emissions, it is necessary to evaluate the effectiveness of each of the schemes in reducing carbon emissions when applied to HESC. Therefore, this paper focuses on a designing sustainable HESC considering various carbon schemes.

HESC is also exposed to several uncertainties such as coal mining rate, biomass yield rate and electricity conversion rate. Therefore, it is important to consider these uncertainties when designing a HESC. A stochastic mixed integer linear programming (SMILP) model is proposed to design a sustainable HESC under uncertainties. The proposed SMILP model aims to improve economic benefits (cost) under the various carbon emission schemes discussed above, namely carbon cap and trade, carbon cap, and carbon tax. The research fills a gap in the literature in the following ways: (1) it considers both coal- and biomass-based electricity plants while designing HESC; (2) the study considers several carbon emission

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schemes – such as carbon cap and trade, carbon cap, and carbon tax – while designing HESC; and (3) uncertainties such as coal mining rate, biomass yield rate and electricity conversion rate are considered.

The remainder of the paper can be outlined as follows: Section 2 presents a comprehensive literature review on electricity supply chain and carbon emission schemes. Section 3 presents the problem statement. Section 4 presents the proposed methodology. Section 5 presents the case study. Section 6 presents the results. Section 7 presents the sensitivity analysis and Section 8 presents the conclusions and future directions.

2. Literature

This section presents the up-to-date literature on coal-based electricity generation, biomass-based electricity generation and carbon emission schemes.

2.1. Coal-based electricity generation

In recent years, a significant amount of literature related to coal-based electricity generation has focused on reducing carbon emissions. Koornneef et al. (2008) conducts a life cycle assessment (LCA) of coal power plant with and without carbon capture and storage technology. The results indicate substantial decrease in carbon emissions for power plant with carbon capture and storage technology. Cui et al. (2012) consider an LCA to estimate the environmental impact of three coal-based electricity generation scenarios in China. An optimizing method is used to calculate the net coal consumption efficiency, reusing coal ash as building material, and increasing desulfurization and denitrization system efficiency. A key managerial insight is that decreasing the road transport distance from the coal supplier to the buyer is essential for reducing the overall environmental impact of electricity generation. Han et al. (2012) develop a multi-objective optimization model for sustainable electricity generation and carbon infrastructure design. The objective is to maximize profit and minimize financial risk taken in reducing carbon emissions. The results provide recommendations for the optimal technology needed produce electricity along with strategies to mitigate carbon emissions. Whitaker et al. (2012) conducts a review on the LCA of coal-based electricity generation. The authors found 270 references to this subject in the literatures, finding that estimated GHGs from coal plants vary from 675 to 1689 grams CO_2-equivalent per kilowatt-hour. The study indicates that this variation is due to various coal plant configurations such as subcritical pulverization, integrated gasification combined cycle, and supercritical pulverized coal combustion. Liang et al. (2013) conduct an LCA for clean coal technologies in China. The results indicate that carbon capture and sequestration technology can significantly reduce carbon emissions, although higher amount of carbon emissions are generated by carbon capture and storage through extra energy consumption. van der Wijk et al. (2014) develop a simulation model to evaluate the effectiveness of carbon capture and storage at coal-based electricity plants. The results indicate a significant reduction in carbon emissions.

2.2. Biomass-based electricity generation

In recent years, biomass-based electricity generation has gained significant attention as it is both renewable and environmentally friendly. Most of the literature related to biomass-based electricity generation has been focused on biomass availability in order to fill electricity demand. Evans et al. (2010) assess the electricity generation from biomass from a sustainability perspective. Parameters such as price, efficiency, GHG emissions, availability, limitations, land use, water use and social impacts are considered in this study. The results show that biomass-produced electricity provides favorable price, efficiency, and emissions, with an unfavorably high land and water usage. Viana et al. (2010) conducts a geographical information system (GIS) based analysis for availability and location of wood-based electricity generation. The result shows the need for alternative fuel in order to meet electricity demand for several regions in Portugal. Dasappa (2011) explores the potential for biomass-based electricity generation in Africa. The study shows that 5000 Megawatt (MW) of electricity can be generated by using 30% of agro-processing residues. In addition, 10 000 MW of electricity can be produced by using 10% forest residues. Shafie et al. (2012) investigate the biomass availability for electricity generation in Malaysia. The study indicates that the effective use of biomass, such as agricultural crop residues and industrial crop waste can help meet the future electricity requirements. Akgul et al. (2014) develop a mixed integer nonlinear programming model to design a carbon-negative biomass-based electricity supply chain. The objectives considered are cost and carbon emissions. The result indicates that higher carbon prices can significantly reduce the carbon emissions of the biomass electricity supply chain. In addition, higher biomass availability can reduce the cost of carbon-negative electricity generation. The LCA study conducted by Röder et al. (2015) shows biomass-based electricity generation can reduce GHGs by 83% compared to coal-based electricity generation. Shabani and Sowlati (2016) present a novel hybrid multi-stage stochastic programming-robust optimization model to design a cost-effective biomass-based electricity supply chain under uncertain conditions. The study illustrates the significant trade-off between profit and quality levels of biomass-based electricity generation.

2.3. Carbon emission schemes

In recent years, a significant amount of research has been conducted addressing various carbon emission schemes in the supply chain area. However, very few studies have incorporated carbon emission schemes in the electricity supply chain. Bird et al. (2011) develop a simulation based Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) model. The simulation model focuses on developing least cost electricity generation portfolio (a combination of electricity sectors) required to meet electricity demand under various carbon emission policies. Considine and Larson (2012) develop an econometric model that examines fuel switching in electricity production under CCTSs. The study indicates that carbon prices significantly impact fuel selection. Zhang et al. (2012) develop a deterministic optimization model in order to plan electricity generation from 10 power sectors in China under various carbon emission schemes. The study provides optimal electricity production allocations for various sectors under different carbon emission schemes.

A review of the literature suggests that none of the studies have focused on designing a hybrid electricity supply chain where coal and biomass are used for electricity generation while simultaneously considering carbon emissions and uncertainties. Therefore, this paper focuses on designing a HESC in which both coal- and biomass-based electricity plants are considered. In addition, various carbon emission schemes, such as carbon cap and trade, carbon cap, and carbon tax, are considered. Uncertainties such as coal mining rate, biomass yield rate, and electricity conversion rate are also considered.

3. Problem statement

This paper focuses on designing an optimal HESC where coal and biomass are considered for electricity generation under carbon emission schemes and uncertainties. Fig. 1 presents the structure

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