Applied Energy 220 (2018) 723–734

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Economic optimization of integrated network for utility supply and carbon dioxide mitigation with multi-site and multi-period demand uncertainties

Yuchan Ahn[a], Jeehoon Han[a,b,*]

[a] School of Semiconductor and Chemical Engineering, Chonbuk National University, 54896, Republic of Korea
[b] School of Chemical Engineering, Chonbuk National University, 54896, Republic of Korea

HIGHLIGHTS

- Integrated model is developed for utility supply and CO_2 mitigation strategies.
- Multi-site and multi-period planning problems are considered.
- Uncertainty in both demands is applied for more realistic approach.
- Two-stage stochastic model is formulated using MILP.

ARTICLE INFO

Keywords:
Supply chain network
Optimization
Stochastic programming
Utility supply
CO_2 mitigation
Uncertainty

ABSTRACT

This study develops a two-stage stochastic model to design an integrated network that simultaneously optimizes utility supply and CO_2 mitigation strategies under demand uncertainties. The objective of the proposed model is to minimize the expected total cost of the integrated network to meet both uncertain demands (utility supply and CO_2 mitigation) for multi-site companies in an industrial complex over a multi-period planning horizon. This model determines the optimal locations and amounts of: (1) utility (steam) transferred between companies; (2) CO_2 captured, transported, and stored; (3) carbon credits imposed on companies that exceed allowable CO_2 emission. The proposed model is applied to Yeosu industrial complex in Korea to validate the model. Total cost for U_2C_2 stochastic model (US\$ 189.92 × 10^6/y) is 0.71% (US\$ 1.34 × 10^6/y difference) higher than the deterministic model (US\$ 188.59 × 10^6/y). The variation of both uncertain demands in the stochastic model affects the cost and structure of integrated network compared to the fixed parameters in the deterministic model, and it confirmed that the uncertainty of demand for utility supply has a more considerable influence on the structure of the integrated network than the demand for CO_2 mitigation.

1. Introduction

Carbon dioxide (CO_2) must be reduced to counteract global warming, which has triggered global efforts [1–3]. Large amounts of CO_2 have been emitted by production of many commodity chemicals or consumption of fuels by the industrial complex (IC), concurrent with consumption of significant amounts of energy [4–6]. Utilities such as steam, water, and electricity account for a substantial portion of energy used in the IC [7–9]. Thus, CO_2 emission is intimately related to utility consumption in the IC. Many studies have been conducted to reduce utility consumption by increasing energy efficiency of units (process, equipment, and plant) or integrated with other processes in same plants, with the indirect benefit of reducing CO_2 emission [10–13]. In corn-based ethanol plants, energy and water consumption could be reduced by energy optimization with the reuse and recycle of process cooling water and steam [14]. Distillation system is highly intensive energy process, which contributes to CO_2 emission. By integrating the gas turbine with distillation system, the existing crude oil installations can save up and reduce the CO_2 emission [15]. By using scheduling algorithms, the reduction of energy consumption have been conducted in many plants for the optimization of the production scheduling of a single machine [16], of operation scheduling of multi-hydraulic press system [17], of solution algorithm for wind power and energy storage system [18], and of energy efficiency in scheduling crude oil operations of refinery [19].

As an alternative to reduce the energy consumption with the indirect benefit of reducing CO_2 emission, the supply chain management, which could be presented as an integrated network for the

* Corresponding author at: School of Semiconductor and Chemical Engineering, Chonbuk National University, 54896, Republic of Korea.
E-mail address: jhhan@jbnu.ac.kr (J. Han).

https://doi.org/10.1016/j.apenergy.2018.02.129
Received 13 December 2017; Received in revised form 14 February 2018; Accepted 18 February 2018

transportation, production, storage, and distribution of materials and products to determine the optimal results [20–22], have applied to the many studies [8,23–27]. Product recovery optimization has confirmed in the closed-loop supply chain to improve sustainability in production process, simultaneously maximizes profit and minimize the energy consumption costs [28]. At a multi-site pulp company, integrated planning of the supply chain have used to consider energy possibility to sell energy products and energy carriers, and this model solved by using mixed-integer linear programming (MILP) [29]. The integrated problem of closed-loop supply chain network design is modeled and optimized to minimize costs of supply, purchasing, operating the disassembly line using nonlinear mixed integer mathematical model, simultaneously considering using tactical level decisions related to midterm decisions [30]. A data envelopment analysis-based framework have developed to meet the target goal of CO_2 mitigation in China for improving their energy performance by projecting onto the efficient frontier in a single move [31]. However, the ability of this indirect reduction meet the CO_2 mitigation targets is limited by the need to maximize energy efficiency. Therefore, direct reduction techniques should be deployed to improve total CO_2 reduction in the IC.

Carbon capture and storage (CCS) system is the primary technique for direct reduction of CO_2 emitted by burning fossil fuels [32–36]; CCS is a chain of processes to capture CO_2 directly emitted from a company and to transport it to a storage site. Many types of CCS system are presented as follow: (1) post-combustion [37]; (2) pre-combustion [38]; (3) oxyfuel combustion [39]; (4) chemical looping combustion [40]. Absorption technology based on monoethanolamine (MEA) in post-combustion is widely used for CO_2 capture, but MEA regeneration requires large amounts of heat [41–43]. Moreover, the captured CO_2 is compressed to near supercritical pressure for its economic transport [44,45]; this process increases electricity use. Deploying a CCS system in the IC increases costs as a result of additional utility consumption and CO_2 emission. As an alternative to meet the CO_2 mitigation target, a carbon-credits trading (CCT) system can be used [46–48]. CCT is a form of emissions permit trading which entities (countries or industries) that emit excessive CO_2 can purchase the right to emit CO_2 from entities that emit little CO_2 [49]. The CCT can be more efficient than the CCS for a company relatively emitting less CO_2 and consuming utility in the IC.

Previous studies have developed the mathematical models to find the optimal solution to minimize total cost to meet the utility supply demands of various emission sources in the IC [50]. A proposed deterministic model [50] to reduce total utility supply cost attempt to maximize energy efficiency by design of a utility supply network that consists of utility source companies (that generate utilities) and sink companies (that need utilities) in the IC. The model was later expanded to consider an integrated network that includes a CO_2 mitigation network that uses CCS and CCT [51]. These models both confirmed cost-effective interconnections between both networks in the deterministic model. However, the previous studies [50,51] assumed that all parameters were constant over the multi-period planning horizon; the realism of the results can be increased by considering the possible variation of some parameters in the model [52–55]. For example, the amounts of CO_2 emission in the product stream can vary due to the change in the quality or quantity of the raw material used in the process, and this variation also affects utility requirements for the process. Therefore, development of an integrated model that considers both uncertain demands (utility supply and CO_2 mitigation demands) is required to observe variation in a model structure.

In this study, the challenge of novelty, which has not been taken into consideration in the previous studies, was addressed. Mathematical model with integration between utility supply and CO_2 mitigation strategies is developed for more realistic approach with the two following issues; (1) multi-site and multi-period planning problems; (2) uncertainty in both demands. The integrated network can help to make a decision on supply chain network problems as an optimal way of an integrated network to meet both uncertain demands in an IC. This study is organized as follows to present the novel challenges: a stochastic model under both uncertain demands is developed for the optimal design of an integrated network as multi-site and multi-period planning problems. The goal of the model is to minimize the expected total cost of the integrated network, subject to satisfies these both uncertain demands for multi-site companies in the IC over a multi-period planning horizon. The proposed model is a two-stage stochastic model formulated using MILP. The locations and amounts of CO_2 treated by CCS or CCT can be determined, as can the locations and amounts of utilities transferred among companies. Section 2 presents the problem statement of the model. Section 3 describes model formulations of objective and constraints to application of both uncertain demands. Section 4 applies case studies to validate the model for the IC. Section 5 presents the results and discussion of techno-economic assessment of the IC using the model. Section 6 presents conclusions.

2. Problem statement

This study finds an optimal framework that uses techno-economic assessment to decide between utility supply and CO_2 mitigation strategies, under multi-level decision criteria such as multi-scenario uncertain demands over the multi-period planning horizon. The novelty of the decision-making model in this study is that the decision framework considers two types of uncertain parameters, which exist in each decision level individually. Details of the decision-making problem are as follow: the network model (Fig. 1) considered in this study consists of a source company with sub-nodes such as chemical plant, utility system, and CO_2 mitigation systems (CCS, CCT), and a sink company with the same sub-nodes excluding the utility system. Here, the sink company needs external assistance to meet its utility demands.

The chemical plant consumes utilities (steam, water, and electricity) to produce target products and concurrently emits CO_2 into the atmosphere. Therefore, a chemical plant is represented as a utility sink (demand) and a CO_2 source (Fig. 1). If CO_2 emitted exceeds the regulation level assigned to each company, CO_2 should be treated using CCS or CCT. CCS is a system that directly captures, transports and stores a physical form of CO_2 to sequester the excess CO_2 generated by each company. CCS itself consumes utilities and emits CO_2. In contrast, CCT system pays a fee for excess CO_2 emission. CCS and CCT systems are considered to be CO_2 sinks (demands), but only the CCS system is considered to be a utility sink (demand). Thus, utility supply and CO_2 mitigation strategies have an interconnectivity problem in an integrated network.

The decision-making problem of a mathematical model for the integrated network determines the following variables; the location and amount of (1) utility (steam) transferred among companies; (2) CO_2 captured, transported, and stored by CCS system and (3) carbon penalties imposed by CCT on companies that exceed allowable CO_2 emission, to ensure that the company meets CO_2 mitigation demands.

The purpose of this study is to minimize total expected value of the cost distribution over a given planning horizon. The model considers a finite set of time periods t and uncertain scenarios z. This model is based on the following assumptions; (1) the network is operated over multi-periods; (2) during each period, the company achieves expected utility supply and CO_2 mitigation demands. In this model, utility supply and CO_2 mitigation demands for each company are uncertain, but all other parameters are deterministic.

In the next section, we will develop an integrated network structure with a multi-period stochastic model to analyze how the uncertain utility supply and CO_2 mitigation demands affect the strategy recommendations compared to the previous multi-period deterministic model. The technical details of the utility and CCS systems are described in the supplementary materials (Figs. A1 and A2 in ESI).