Journal of Environmental Management 215 (2018) 305–315

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

An optimization model for carbon capture & storage/utilization vs. carbon trading: A case study of fossil-fired power plants in Turkey

Semra Ağralı [a], Fehmi Görkem Üçtuğ [b, *], Burçin Atılgan Türkmen [c]

[a] MEF University, Faculty of Engineering, 34396, Maslak, İstanbul, Turkey
[b] İzmir University of Economics, Faculty of Engineering, Sakarya Caddesi No: 156, 35330, Balcova, İzmir, Turkey
[c] Bilecik Şeyh Edebali University, Department of Chemical Engineering, 11230, Gulumbe, Bilecik, Turkey

ARTICLE INFO

Article history:
Received 29 July 2017
Received in revised form
7 March 2018
Accepted 12 March 2018

Keywords:
Carbon capture and storage
Carbon capture and utilization
Coal-fired power plant
Mixed integer programming
Optimization
Turkey

ABSTRACT

We consider fossil-fired power plants that operate in an environment where a cap and trade system is in operation. These plants need to choose between carbon capture and storage (CCS), carbon capture and utilization (CCU), or carbon trading in order to obey emissions limits enforced by the government. We develop a mixed-integer programming model that decides on the capacities of carbon capture units, if it is optimal to install them, the transportation network that needs to be built for transporting the carbon captured, and the locations of storage sites, if they are decided to be built. Main restrictions on the system are the minimum and maximum capacities of the different parts of the pipeline network, the amount of carbon that can be sold to companies for utilization, and the capacities on the storage sites. Under these restrictions, the model aims to minimize the net present value of the sum of the costs associated with installation and operation of the carbon capture unit and the transportation of carbon, the storage cost in case of CCS, the cost (or revenue) that results from the emissions trading system, and finally the negative revenue of selling the carbon to other entities for utilization. We implement the model on General Algebraic Modeling System (GAMS) by using data associated with two coal-fired power plants located in different regions of Turkey. We choose enhanced oil recovery (EOR) as the process in which carbon would be utilized. The results show that CCU is preferable to CCS as long as there is sufficient demand in the EOR market. The distance between the location of emission and location of utilization/storage, and the capacity limits on the pipes are an important factor in deciding between carbon capture and carbon trading. At carbon prices over $15/ton, carbon capture becomes preferable to carbon trading. These results show that as far as Turkey is concerned, CCU should be prioritized as a means of reducing nation-wide carbon emissions in an environmentally and economically rewarding manner. The model developed in this study is generic, and it can be applied to any industry at any location, as long as the required inputs are available.

1. Introduction and literature review

Greenhouse gas (GHG) emissions have been increasing steadily since the beginning of industrial revolution. Over the last decade, annual GHG emissions have increased by an average of 2.7% (Cuéllar-Franca and Azapagic, 2015). Since 1990s two major worldwide gatherings took place, one in Kyoto and the other one in Paris, in 1997 and 2015, respectively. In these meetings, it has been scientifically suggested that the average global temperature increase as a result of climate change should be limited to no more than 2°C in order to avoid catastrophic outcomes (Voll et al., 2012). According to IPCC (2013), in order to reach this target, worldwide GHG emissions must be lowered by at least 50% of their current values by 2050. Although there are several gases which act as GHGs, the most common and well-known of these gases is carbon dioxide (CO_2). Concentration of CO_2 has increased from 280 parts per million by volume (ppmv) at the pre-industrial level to 395 ppmv at present, and it is estimated to reach to a level of 570 ppmv by the end of this century (Goel et al., 2015). Fossil fuels provide more than 85% of the worlds primary energy, and also contribute to global GHG emissions in similar proportions (Hasan et al., 2015). Therefore, reducing global CO_2 emissions resulting from fossil fuel

---

* Corresponding author.
E-mail addresses: gorkem.uctug@yahoo.com, gorkem.uctug@ieu.edu.tr (F.G. Üçtuğ).

https://doi.org/10.1016/j.jenvman.2018.03.054
0301-4797/

utilization is of utmost importance for environmental sustainability.

1.1. Carbon capture

Governments can enforce different approaches and techniques to reduce CO_2 emissions, such as increasing the penetration of clean energy technologies like wind, solar, and even nuclear; promoting energy conservation and efficiency; and also a more direct approach named carbon capture (Viebahn et al., 2007). Carbon capture involves the direct removal of CO_2 from the GHG-emitting system before the emission actually takes place. There are three main methods of capturing CO_2, whose basic definitions are provided below (Markewitz et al., 2012):

i *Post-combustion capture*: the capture of CO_2 from the flue gas stream after combustion;
ii *Pre-combustion capture*: obtaining synthesis gas (a mixture of CO_2 and hydrogen gas) from the fuel prior to combustion by a chemical method such as gasification or reforming, and then capturing CO_2 from this mixture;
iii *Oxyfuel capture*: using (nearly) pure oxygen to combust the fuel so that the flue gas will have a high CO_2 concentration, which makes separation relatively easy.

Once captured, CO_2 needs to be dehydrated, purified, and compressed to get rid of impurities such as oxygen gas, nitrogen gas, or water (Porter et al., 2017). We summarize the main stages of the above-mentioned three carbon capture methods in Fig. 1. Once a high-purity stream of CO_2 is obtained, it can either be stored for long term or it can be utilized in an industrial process. The former approach is known as carbon capture and storage (CCS) whereas the latter approach is named carbon capture and utilization (CCU). Storage options for CCS include geological storage, in which CO_2 is buried underground, or ocean storage. As far as CCU is concerned, we can utilize CO_2 for various processes such as mineral carbonation, using it as a chemical feedstock for the production of chemicals such as methanol, or enhanced oil recovery in which CO_2 and water are alternately injected into a reservoir of oil so that the oil can move towards the production wells (Cuéllar-Franca and Azapagic, 2015; Santos, 2015; Zhang and Huisingh, 2017).

Both CCS and CCU face technical, economic, and environmental challenges. For instance, both CCS and CCU are extremely capital-intensive, difficult to integrate into an already-functioning power generation system, and long-term storage of carbon underground or in the oceans may lead to environmental hazards (Arranz, 2015; Hasan et al., 2015; Kruger, 2017). Therefore, the decision-making process prior to the investment as well as operational planning for a CCS/CCU system have significant economic and environmental consequences. Just like any other investment, the capital investment and operational expenses of CCS/CCU systems increase with the size of the systems. On the other hand, high CCS/CCU system capacity would lead to capturing more CO_2, which then can be sold in a voluntary or obligatory carbon market or can be utilized in another technological process. Both of these paths will increase the revenue. Consequently, increasing the amount of CO_2 captured would increase the cost and the revenue simultaneously, leading to an optimization problem.

1.2. Literature review

We provide the related literature for CCS and/or CCU systems in this section. Hasan et al. (2015) present a hierarchical and multiscale framework to design CCS and CCU supply chain networks with minimum investment, operating and material costs by taking into consideration the selection of source plants, capture processes, capture materials, CO_2 pipelines, locations of utilization (for enhanced oil recovery) and sequestration sites, and amounts of CO_2 storage. Their optimized network achieves a profit of $9.23 per ton of CO_2. Rao and Rubin (2006) develop an integrated modeling

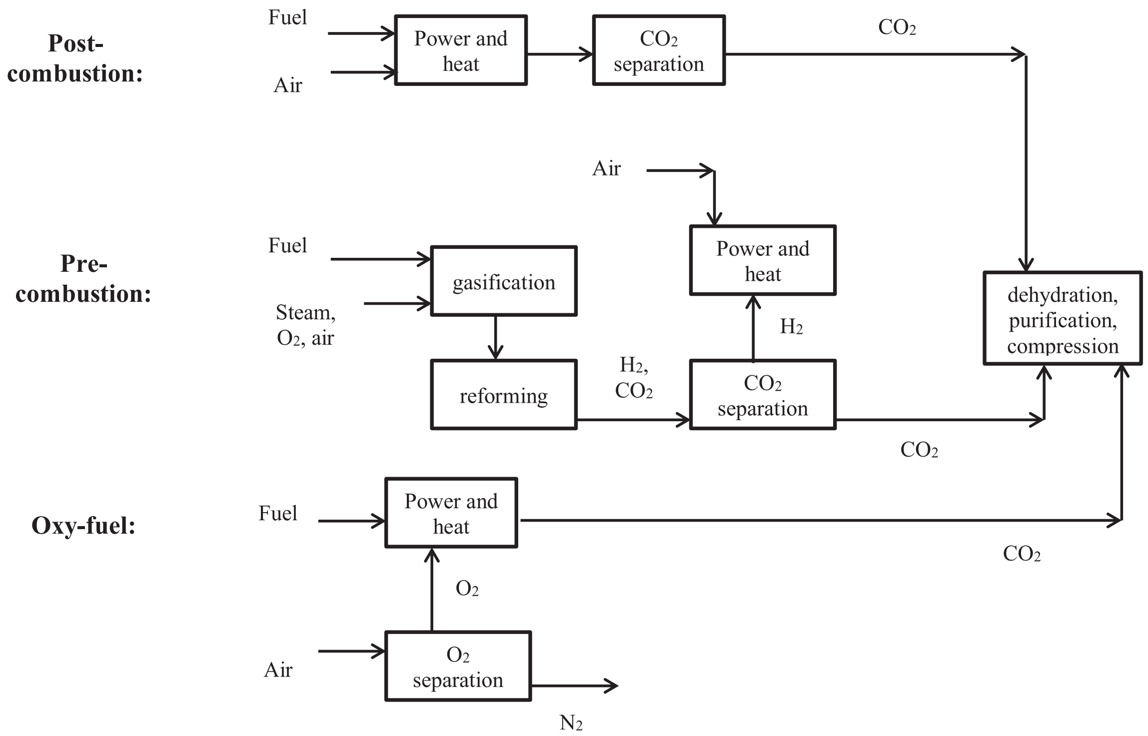

Fig. 1. Basic principles of carbon capture.