An Optimization Model for Carbon Capture & Storage/Utilization vs. Carbon Trading: A Case Study of Fossil-Fired Power Plants in Turkey

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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 helps to make this decision. 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 in the emissions trading system, and finally the negative revenue of selling the carbon to other entities companies 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 more preferable than CCS as long as there is sufficient demand in the EOR market. The distance between the location of emission and location of utilization/storage is an important factor in deciding between carbon capture and carbon trading. At carbon prices over

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\$15/ton, carbon capture is preferable over 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.
Keywords: Carbon capture and storage; Carbon capture and utilization; Coal-fired power plant; Mixed integer programming; Optimization; Turkey

1. Introduction and Literature Review

Ever since the beginning of the industrial revolution, greenhouse gas (GHG) emissions have been increasing steadily. Over the last decade, annual GHG emissions have increased by an average of 2.7% (Cuéllar-Franca and Azapagic, 2015). GHG emissions lead to the entrapment of excessive amounts of solar irradiation in the atmosphere, thereby causing a phenomenon known as climate change. In order to prevent, or at least minimize, the hazardous impacts of climate change such as the shifting of ocean currents, increase in the sea levels, etc., GHG emissions must be reduced. 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). In order to reach this target, worldwide GHG emissions must be lowered by at least 50% of their current values by 2050 (IPCC, 2013). Although there are several gases which act as GHGs, the most common and well-known of these gases is carbondioxide (CO_2). For this reason, GHG emissions are universally expressed in terms of kg (or tons) of CO_2 equivalents. Concentration of CO_2 has increased from 280 parts per million by volume (ppmv) at the preindustrial 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 utilization is of utmost importance as far as environmental sustainability is concerned.

1.1. Carbon Capture

Different approaches and techniques can be employed 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). The main stages of the above-mentioned three carbon capture methods are summarized in Figure 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, CO_2 can be utilized by various processes such as mineral carbonation, being used 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).

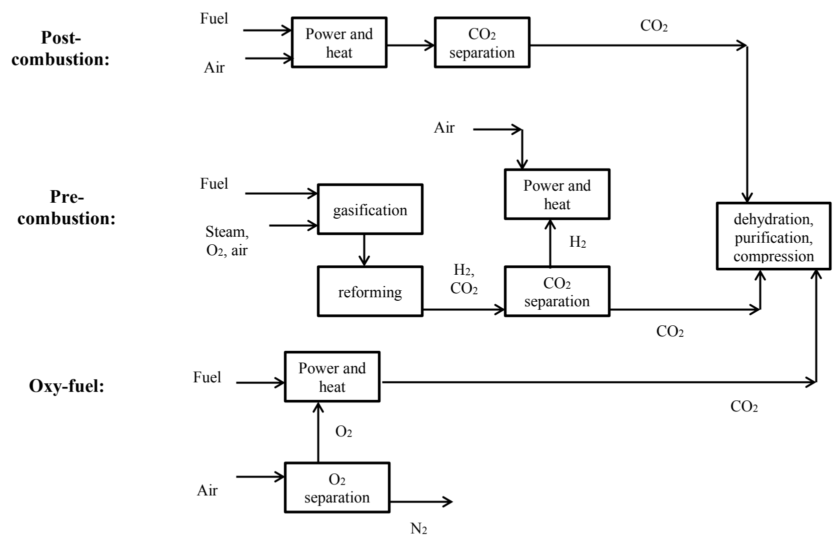

Figure 1: Basic principles of carbon capture

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 has significant economic and environmental consequences. Just like any other investment, the higher the size of the CCS/CCU system, the higher the capital investment and operational expenses would be. On the other hand, increasing CCS/CCU system capacity would lead to more CO_2 being captured, 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. Hence we have an optimization problem in our hand.

1.2. Literature review

As far as previous studies in the literature, which focus on the economic optimization of a CCS and/or CCU system, are concerned, Hasan et al. (2015) presented a hierarchical and multi-scale 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 and sequestration sites, and amounts of CO_2 storage. Their optimized network was found to achieve a profit of \$9.23 per ton of CO_2. Rao and Rubin (2006) developed and integrated modeling framework to identify the most cost-effective level of CO_2 control using currently available amine-based CO_2 capture technology for pulverized coal power plants. Üçtuğ et al. (2014) find an optimal solution to the problem of choosing between CCS and carbon trading for a hypothetical methanol production facility. They used a non-linear optimization approach where the objective was to maximize the net returns from pursuing an optimal mix of CCS and carbon trading. The results were found to be sensitive to carbon credit prices and the discount rate, which determines the choices with respect to the future and the present. Schach et al. (2010) compared three alternative CCS configurations to the benchmark process, which is absorption using monoethanolamine (MEA) as solvent. They concluded that "not the process with the highest energy savings has the lowest cost of CO_2-avoided, but that the influence of rising investment costs of more complex configurations cannot be ignored". Cristóbal et al. (2012b) studied a coal-fired power plant that considers installing four control devices in series, where it is possible to bypass one or more of them, before the CO_2 discharge point. They developed a mixed-integer nonlinear programming (MINLP) model in which they decided on which devices to use and the operating condition of each device. In another paper by the same research group, a similar problem, where a set of pollution control retrofitting alternatives were considered to be installed in a cap and trade framework, was modelled as a MINLP (Cristóbal et al., 2012a).

Santibanez-Gonzalez (2017) compared carbon pricing versus CCS. To that aim, novel stochastic mixed-integer linear optimization model was developed. Their case study involved cement factories in Brazil. When the price of CO_2 reached high values such as \$60/ton, CCS started to emerge as a feasible option, but even then the high cost of infrastructure (mostly piping) was found to favor paying taxes instead of installing a carbon capture system in most cases. Wu et al. (2015) developed an inexact CCS optimization model for supporting regional carbon capture, transportation and storage planning under interval-format uncertainty with a least-cost strategy. Their model was aimed to provide an optimal configuration of capture facilities, transportation infrastructure, and storage options through optimizing decisions regarding sitting, scale, and timing of capture, transport, and storage of CO_2 in a region. Their case study, which involved China, suggested that capture of CO_2 in coal-chemical/liquids/gas and CO_2-enhanced oil recovery (EOR) storage would be convenient for the early-stage commercialization of CCS.

Arnette (2017) developed a model that can compare renewable energy and CCS to determine the optimal combination of these resources to achieve maximum reduction in GHG emissions. After a total of 47 iterations, CCS was found to be implemented five times, with a maximum of 1.71% of a required 30% decrease in carbon emissions. Hence, it was concluded that renewable energy options were more cost-effective means of achieving environmental goals. Ghanbari et al. (2015) worked on the numerical optimization of incorporating CCU into steel manufacturing. Their results include optimal state of operation under periodic conditions, maximizing the net present value, minimizing specific carbon dioxide emissions and fuel consumption in the system. Finally, Ravi et al. (2016) developed a MINLP model that can be used to select appropriate sources, capture technologies, transportation network and CO_2 storage sites and optimize for a minimum overall cost for a nationwide CO_2 emission reduction in the Netherlands. They concluded that the minimum overall cost of all scenarios is 47.8 billion Euros for 25 years of operation and 54 megatons of oil equivalent capture of CO_2. Additionally, it was concluded that pressure swing adsorption is the most efficient CCS technology. Finally, Asghari and Shakouri (2014) developed an economical model in which they find the optimum combination of CCS and CCU by considering different storage options. Variables such as revenue from CCU, carbon credits, distance of storage location to the emission location were considered. Their results showed that CCU is the more preferable choice.

1.3. Motivation of the study

In this study, we developed an optimization-based economic model that determines whether CCS, CCU, a combination of them or no carbon capture at all is a more beneficial option for fossil-fired power plants. The details of the model will be presented in the following section. We implemented the developed model by using data obtained for two lignite-fired power plants located in Turkey. Although the case study in this paper is limited to two lignite-fired power plants in Turkey, as long as the necessary model inputs such as CO_2 emissions for the particular process of interest, the cost data for the chosen CCS/CCU methods, and up-to-date carbon prices are available, our model can be applied to any industry. Hence, the methodology developed as a result of our study is as important as, if not more than, our findings. To the best of our knowledge, there exists no other study in the literature in which CCS, CCU and carbon trading were considered simultaneously as emission reduction strategies via a generic model that is applicable to any industry.

2. Problem Description and Methodology

We give the problem definition and the mathematical model in this section.

2.1. Problem Description

We consider a set of thermal power plants, I, that are located in different regions. These power plants operate in an environment where a cap and trade system is in operation in order to restrict the carbon emission levels of the plants. These plants consider installing carbon capture units throughout a planning horizon that covers a set of years, T, if it is profitable. The carbon capture unit requires an installation cost, $IC(f_i)$, which is a function of the installed carbon capture capacity of the unit, f_i, and an operating cost, $OC(X)$, which depends on the amount of carbon captured, X (X value is explicitly written in the objective function, see Equation (1)).

The power plant has the option of not installing a carbon capture unit; and therefore, if the emission level of the plant is above its cap value, then they have to buy the surplus credits from other entities. On the other hand, if they choose to install the carbon capture unit and capture some amount of carbon, then they have two options, which can be used in different combinations: (1) sell the captured carbon to entities, L, that will utilize the carbon for different processes, such as enhanced oil recovery, produce carbonated soda, etc., at a price of p_t^C in year t; and (2) transport the captured carbon to a storage site to be stored at a unit cost of S_i^{CS}. The unit transporation cost to the storage site and to entity $l \in L$ are given by TC_i^{CS} and TC_{il}^{CU}, respectively. If the carbon emission level of the plant is below its cap value, then they are also entitled to sell the surplus value at the emissions trading system at a price of p_t^E in year t.

The power plant $i \in I$ has different decisions to make in year $t \in T$: (i) either install a carbon capture unit, $s_{it} = 1$, or not, $s_{it} = 0$; (ii) the amount of carbon captured and transported to a storage site, x_{it}; (iii) the amount of carbon captured and sold to entity $l \in L$, k_{ilt}; and finally (iv) the amount of carbon that will be either bought or sold at the emissions trading system, y_{it}. All these symbols with their definitions are provided in Table 1

2.2. Mathematical Model

We develop a mixed-integer programming model that aims to minimize the cost of decisions on the carbon capture unit for a set of thermal power plants. We provide the objective function of the model in Equation (1)

Table 1: Nomenclature

Symbol	Description
T	set of planning years
I	set of power plant locations
L	set of entities that are willing to utilize the captured carbon
d_i^S	the distance from power plant $i \in I$ to the storage site (km)
d_{il}^U	the distance from power plant $i \in I$ to entity $l \in L$ (km)
p_t^C	the price of carbon that is sold to an entity in year $t \in T$ (\$/ton)
p_t^E	the price of carbon in the emissions trading system in year $t \in T$ (\$/ton)
k_l^{lim}	upper bound on the amount of carbon that can be sold to entities (ton)
m_{it}	amount of carbon produced at power plant $i \in I$ during year $t \in T$(ton)
cap_{it}	cap value on the emissions level of power plant $i \in I$ at year $t \in T$ (ton)
cp_i	power generation capacity of power plant i (MW)
$IC(f_i)$	installation cost of a carbon capture unit to a power plant with power generation capacity of cp_i (\$/MW)
OC	unit operating cost of a carbon capture unit (\$/ton)
TC_i^{CS}	transportation cost of carbon captured at power plant $i \in I$ and sent to storage site (\$/ton)
S^{CS}	unit cost of carbon storage (\$/ton)
TC_{il}^{CU}	transportation cost of carbon captured at power plant $i \in I$ and transported to entity $l \in L$ (\$/ton)
f_i	the capacity of the carbon capture unit installed at power plant $i \in I$ (ton)
s_{it}	=1, if a carbon capture unit is installed at power plant location i in year $t \in T$; =0, otherwise
y_{it}	amount of carbon generated at power plant location i and traded at the emissions trading system in year t
x_{it}	amount of carbon captured at power plant location i for storage in year t
x_i^{max}	maximum amount of carbon transported to a storage site throughout the planning horizon (ton)
k_{ilt}	amount of carbon captured at power plant location i and sold to entity $l \in L$ for utilization in year t
k_{il}^{max}	maximum amount of carbon transported to entity $l \in L$ throughout the planning horizon (ton)

$$\text{Min} \quad z = \sum_{t\in T} \frac{1}{(1+r)^t} \Bigg[\sum_{i\in I} IC(f_i)s_{it} + \sum_{i\in I} OC \left(x_{it} + \sum_{l\in L} k_{ilt} \right) + \sum_{i\in I} S^{CS} x_{it} + \sum_{i\in I} \left(TC_i^{CS}(x_i^{max}, d_i^S)s_{it} + \sum_{l\in L} TC_{il}^{CU}(k_{il}^{max}, d_{il}^U)s_{it} \right) + \sum_{i\in I} p_t^E y_{it} - \sum_{i\in I}\sum_{l\in L} p_t^C k_{ilt} \Bigg] \tag{1}$$

Equation (1) minimizes the net present value of (i) the installation cost of the carbon capture unit, (ii) the operating cost of the unit, (iii) the storage cost of the carbon captured and transported to a storage site, (iv) the total transportation cost of carbon to storage sites and to entities for utilization, (v) the cost (or revenue) that results in the emissions trading system, and finally (vi) the negative revenue of selling the carbon to companies for utilization. Note that the investment cost, $IC(f)$, and the operating cost, $OC(x_t + k_t)$ can be any type of function depending on the carbon capture capacity of the unit and the amount of carbon captured at the unit at a time period, respectively. The transportation and storage costs are taken as linear functions of the distance carbon is transported.

Constraint set (2) determines the capacity level of the carbon capture unit if it is installed:

$$f_i \geq x_{it} + \sum_{l\in L} k_{ilt}, \quad \forall i \in I, t \in T. \tag{2}$$

Note that since the objective is a minimization function, in the optimal solution the capacity level, f, will be equal to the maximum amount of carbon captured over the planning horizon, i.e. $f_i = \max_{t\in T}\{x_{it} + \sum_{l\in L} k_{ilt}\}$.

The company needs to install a pipeline either to the storage site or to the entity to which the carbon will be sold. These pipelines should be installed with a capacity sufficient to transport the captured carbon. Constraints (3) and (4) determine the maximum amount of carbon that will be sent via pipeline to the storage site and the entity for utilization, respectively:

$$x_i^{max} \geq x_{it}, \quad \forall i \in I, t \in T; \tag{3}$$

$$k_{il}^{max} \geq k_{ilt}, \quad \forall i \in I, l \in L, t \in T. \tag{4}$$

Note that the decision on installing a pipeline and a carbon capture unit are made simultaneously at any time period during the planning horizon.

Constraint set (5) ensures that the sum of the amount of carbon captured for storage and for utilization, and the amount of carbon traded at the emissions trading system is equal to the total emission level of the power plant less the cap value assigned to the company at a given year:

$$x_{it} + \sum_{l \in L} k_{ilt} + y_{it} = m_{it} - cap_{it}, \quad \forall i \in I, t \in T. \tag{5}$$

Note that y_{it} will be defined as an unrestricted variable; and if the company is entitled to sell the amount of carbon that is below the cap value, y_{it} will take a negative value. On the other hand, if the emission level of the company is above its cap value, then y_{it} will take a positive value. In the objective function (1), when y_{it} is negative, the company will make money as a result of selling the surplus value at the emissions trading system.

The carbon capture unit can capture carbon only if the corresponding capture unit is installed either in that year or in one of the previous years. This is provided by Equation (6):

$$x_{it} + \sum_{l \in L} k_{ilt} \leq m_{it} \sum_{t' \leq t} s_{it'}, \quad \forall i \in I, t \in T. \tag{6}$$

Constraint set (6) also ensures that the plant cannot sell and store more than the amount of carbon that is generated.

We assume that there is a limit over the amount of carbon that is sold to each entity $l \in L$ for utilization, k_l^{lim}, which is determined exogenously. This is satisfied by Equation (7):

$$\sum_{i \in I} k_{ilt} \leq k_l^{lim}, \quad \forall l \in L, t \in T. \tag{7}$$

Finally, a carbon capture unit can be installed in a power plant only once during the planning period. This is provided with Constraint set (8)

$$\sum_{t \in T} s_{it} \leq 1, \quad i \in I. \tag{8}$$

Note that, since it is a cost minimization problem, Constraint set (8) is redundant. However, we would like to add it for other researchers that may use our model in another context.

We write our mixed-integer model as follows:

$$\begin{aligned} \text{Minimize} \quad & (1) \\ \text{Subject to} \quad & (2) - (8) \\ & x_{it}, k_{ilt}, f_i \geq 0, \quad \forall i \in I, l \in L, t \in T, \\ & s_{it} \in \{0, 1\}, \quad \forall i \in I, t \in T. \end{aligned}$$

3. Case Study

We applied the mathematical model provided in the previous section to power plants located in Soma and Afşin, Turkey. We first provide the related data, and then give our analysis in this section.

3.1. Definitions and Related Data

We consider two power plants located in Soma (west of Turkey) and Afşin (southeast of Turkey). The reason for the selection of these two particular power plants in the case study is as follows: As indicated in Sections 1 and 2, distance between the point of emission and point of storage/utilization is one of the most important criteria as far as optimization models about carbon capture are concerned. Soma and Afşin plants are far away from each other, and the former is close to the point of storage whereas the latter is close to the point of utilization. Therefore, we decided that the effect of distance can easily be investigated if we studied those two power plants. These power plants are lignite-fired power plants with installed capacities of 1000MW and 1800MW, respectively. Both plants operate with a capacity factor of 85%. Although there is currently no carbon emissions trading system in operation in Turkey, the Directorate General of Environmental Management under the Ministry of Environment and Urbanization is currently investigating an emission trading system to be put into operation in near future (MEU, 2012). Therefore, the power plants that we analyze are considering to build carbon capture units to operate under a functional cap and trade system. If a carbon capture unit is installed, then there exist two options for the carbon captured: (1) install a pipeline from power plants to the nearest storage site: these sites are Mediterranean Sea (under deep sea level 50 km away from the shoreline) and salt lake for Afşin and Soma, respectively; (2) sell the carbon captured to the oil companies located in Mosoul, Iraq, to be used in EOR. Since Mosoul is geographically the closest place to Turkey that has major oil production sites, we chose Mosoul for carbon utilization location.

We follow the assumptions of Kuckshinrichs and Vögele (2015) while calculating the investment and operating costs of the carbon capture unit. The investment cost depending on the capacity level, f_i, is given as follows:

$$IC(f_i) = 640,800,000 \left(\frac{f_i}{\max_{t \in T}\{m_{it}\}} \right)^{0.6} \tag{9}$$

where 640,800,000 is the capital investment in Dollars required for a reference power plant of similar quality (Rubin et al., 2015); whereas the 0.6 exponent is based on the commonly used "0.6 rule (economies of scale)," which can be described as follows: The price of an industrial equipment can be estimated by multiplying the price of a reference equipment of identical purpose by the 0.6th power of the ratio of the capacities of the actual equipment and the reference equipment (Peters et al., 1968).

The operating cost has a fixed part, which needs to be paid even if the unit is not operational for a time period, and a variable part, which is linear with respect to the amount of carbon captured (Üçtuğ et al., 2014):

$$OC(x_t + k_t) = 600,000 + 3.8(x_t + k_t). \tag{10}$$

We calculate the transportation and storage costs based on the analysis given in Zero Emission Platform (2011). The unit cost of installing onshore and offshore pipeline (\$/ton) depending on the distance, d, are $\frac{5.4d}{180}$ and $\frac{9.3d}{180}$, respectively. We also have annual operation cost for pipelines, which is calculated as 3% of the pipeline installation cost (Knoope, 2015). Finally, for the carbon that is transported to a storage site, the storage cost is \$10/ton of carbon (Voll et al., 2012).

3.2. Sensitivity Analysis

We implement the model given in Section 2 by using the data provided above. We apply sensitivity analysis over the carbon price in the emissions trading system and the maximum limit over the utilizable carbon as these two factors are the ones that affect the optimal decision most compared to other parameters. Table 2 provides the data sets for sensitivity analysis and the optimal decisions. We take the planning horizon as 20 years and the annual interest rate as 5%. Moreover, we assign the cap value to the plants that are equal to their emission value for time 0, and decrease it by 3% from the initial value every following year.

In Table 2, p^E column gives the initial value of the carbon price in the emissions trading system. We increase this value by 3% every year as we expect to have an effective cap and trade system in the future, which will force the carbon price to increase. We take the price of utilizable carbon constant at \$5 throughout the planning horizon. k_1 and k_2 give the amount of carbon that is captured at Soma and Afşin and sold to the company for utilization,

Table 2: Optimal decisions for various scenarios and conditions

k^{lim} ($\times 10^6$ton)	p^E (\$/ton)	p^C (\$/ton)	k_1 ($\times 10^6$ton)	x_1 ($\times 10^6$ton)	k_2 ($\times 10^6$ton)	x_2 ($\times 10^6$ton)	OBJ (\$ $\times 10^6$)
22.5	20	5	7.45	0	13.4	0	-2585
20	20	5	6.6	0.8	13.4	0	-2458
17.5	20	5	4.1	3.3	13.4	0	-2084
15	20	5	1.6	5.9	13.4	0	-1709
12.5	20	5	0	7.4	12.5	0.9	-1317
10	20	5	0	7.4	10	3.4	-877.6
7.5	20	5	0	7.4	7.5	5.9	-438.5
5	20	5	0	7.4	5	8.4	0.6
2.5	20	5	0	7.4	2.5	10.9	439.6
0	20	5	0	7.4	0	13.4	878.7
22.5	15	5	7.45	0	13.4	0	-1416
20	15	5	6.6	0.8	13.4	0	-1289
17.5	15	5	4.1	3.3	13.4	0	-928.6
15	15	5	0	0	13.4	0	-781.1
12.5	15	5	0	0	12.5	0.9	-624.6
10	15	5	0	0	10	3.4	-191.1
7.5	15	5	0	0	7.5	5.9	242.4
5	15	5	0	0	5	8.4	675.9
2.5	15	5	0	0	2.5	10.9	1109
0	15	5	0	0	0	0	1430
22.5	25	5	7.45	0	13.4	0	-3755
20	25	5	6.6	0.8	13.4	0	-3627
17.5	25	5	4.1	3.3	13.4	0	-3253
15	25	5	1.6	5.9	13.4	0	-2878
12.5	25	5	0	7.4	12.5	0.9	-2480
10	25	5	0	7.4	10	3.4	-2041
7.5	25	5	0	7.4	7.5	5.9	-1601
5	25	5	0	7.4	5	8.4	-1162
2.5	25	5	0	7.4	2.5	10.9	-721.9
0	25	5	0	7.4	0	13.4	-282.3

respectively. Moreover, x_1 and x_2 give the amount of carbon captured and sent to storage sites from Soma and Afşin, respectively. Note that the amount of carbon captured at plants and either sold to companies or sent to storage sites do not change from one year to the next. Therefore, we only provide the amounts of carbon for the initial years for both plants. The only difference is for the lines where k^{lim} is between 12.5 and 0, $p^E = 20$ and $p^C = 5$, where the investment for carbon capture unit for Soma is realized at year 3. For all other data sets, if a carbon capture unit is installed, then it is installed at the beginning of the planning horizon.

We provide the amount of carbon sent to a company for utilization versus the amount of carbon sent to storage sites for both plants when $p^E = 20$ and $p^C = 5$ in Figure 2. For every group of stack, the first stack shows the carbon amount for Soma, and the second one is for Afşin. When carbon utilization is not an option, i.e., the maximum allowable limit of carbon that can be sent to a company is zero, then the optimal decision is to install a carbon capture unit and store all emission amount generated by both power plants. On the other extreme when there is no practical limit on the amount of carbon to be utilized, the optimal decision is to utilize all of the generated carbon. In between these scenarios, since the location of the oil production facility, where the CO_2 will be utilized for enhanced oil recovery, is in Mosoul (Iraq) and it is much closer to Afşin power plant than Soma power plant, it is not surprising that utilization is preferred over storage, as the transportation cost for utilization is much less than the cost of transportation and storage in the CCS scenario. If there is a surplus value, then it is optimal to transport more carbon from Soma plant. In all cases, it is optimal to invest in a carbon capture unit. However, when carbon prices fall to $15/ton level, the model suggests the plant in Soma to give up any capture options and compensate the emission of carbon by purchasing credits from other entities. This action does not apply to the plant in Afşin, because the cost of transportation is much lower in Afşin, as indicated above. These results agree with earlier studies in which it was stated that below a certain carbon price, carbon capture of any sort becomes infeasible (Arnette, 2017; Santibanez-Gonzalez, 2017), and carbon trading emerges as the more feasible option (Üçtuğ et al., 2014).

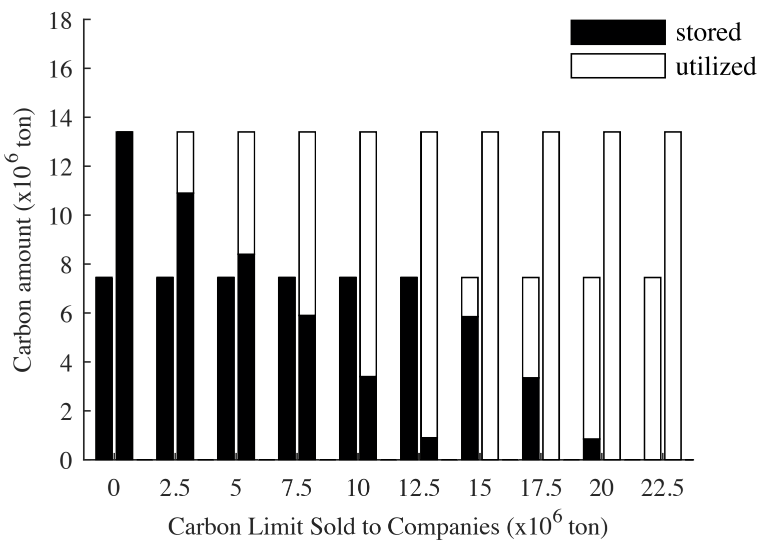

Figure 2: Carbon utilized versus stored

4. Conclusion

In this study we developed a mixed-integer programming model that aims to minimize the cost of decisions on the carbon capture unit for a set of thermal power plants less the revenue that would be obtained by selling carbon to entities and/or in an emissions trading scheme. Based on economic conditions, such as carbon price and carbon cap, the power plant can choose to install a carbon capture unit or not. The latter option involves purchasing credits from other entities involved in the emissions trading scheme so that the power plant can compensate for its above-the-cap emissions. The former option, on the other hand, leads to a further choice-making between utilizing or storing the captured carbon. The factors that determine this particular decision are the carbon price, storage and transportation costs, storage and transportation distances, and the limit over the maximum amount of carbon to be utilized.

Our case study involved two actual coal-fired power plants in Turkey, one in Afşin (southern Turkey) and one in Soma (mid-western Turkey). It was found in the literature that the cost of carbon utilization is less than that of carbon storage, and consequently the model preferred CCU over CCS as long as there was sufficient demand for utilization. Since the only realistic venue for carbon utilization is enhanced oil recovery and there is no large scale oil production in Turkey, it was assumed that the carbon to be utilized would be transported to Iraq. Due to the fact that Afşin is much closer to Iraq when compared to Soma, the overall cost of running a carbon capture unit (regardless of the fate of carbon after being captured) was always higher in the case of Soma. For this reason, at lower carbon prices and low demand for EOR, the model suggests that the plant in Soma should not install a carbon capture unit at all and choose carbon trading as a more feasible option instead. On the other hand, as far as the Afşin plant is concerned, giving up on carbon capture becomes a feasible option only when carbon prices fall to $15/ton and there is zero demand for carbon utilization.

In conclusion our results suggest that as long as there is a realistic demand for EOR, carbon capture and utilization can be a feasible option for Turkish power plants, especially for those located in the southern and southeastern parts. Considering the fact that Turkey has to fulfill certain nationally determined contribution promises as per the Paris agreement of 2015, providing incentives for the rapid penetration of CCU into the market would have significant economic and environmental returns. Therefore, we think that it should be Turkish government's primary goal to set up a functional CCU market between Turkey and its oil-producing neighbors. In the long run, when carbon capture technologies become cheaper and an obligatory carbon market is established in Turkey, CCS and carbon trading would eventually accompany CCU. As a result more and more entities can be involved in emission-reducing activities. The particular model developed in this study can easily be implemented by any entity in any industry, as long as the required data are available.

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