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Research article

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 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

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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 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 (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

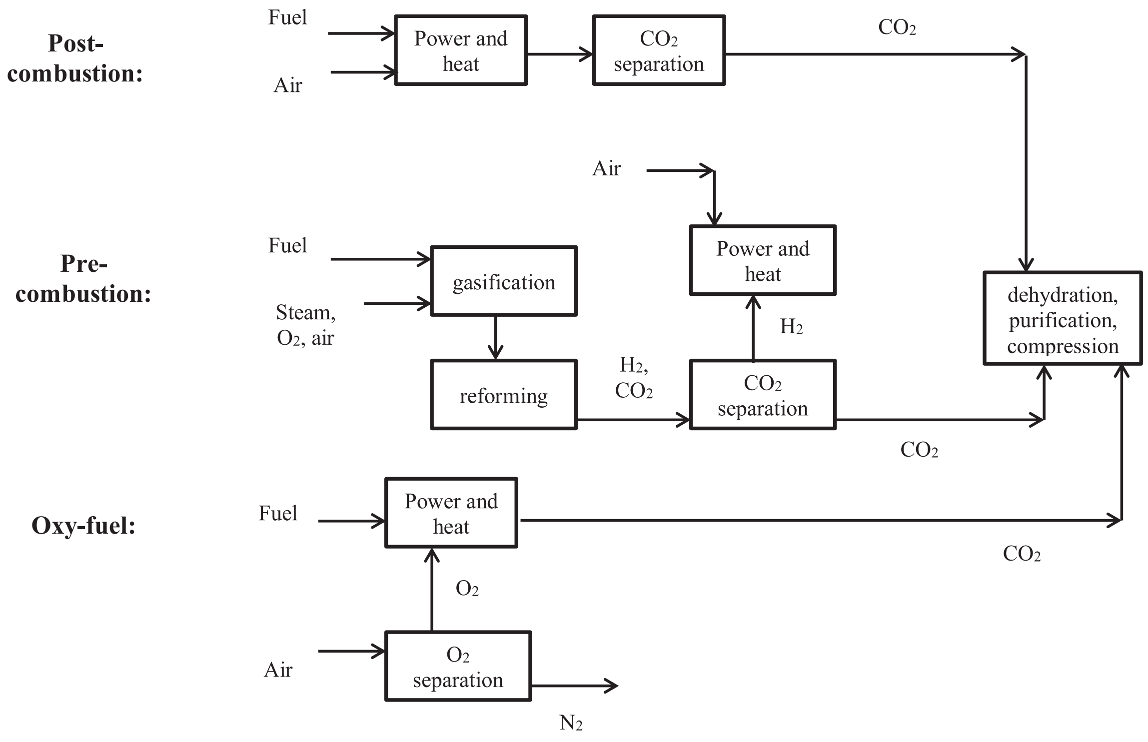


Fig. 1. Basic principles of carbon capture.

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 use a non-linear optimization approach where the objective is to maximize the net returns from pursuing an optimal mix of CCS and carbon trading. The results are 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) compare three alternative CCS configurations to the benchmark process, which is absorption by using monoethanolamine (MEA) as solvent. They conclude that “the process with the highest energy savings is not the lowest cost of CO_2-avoided, and the influence of rising investment costs of more complex configurations cannot be ignored.” Cristóbal et al. (2012b) study a coal-fired power plant for which installing four control devices in series is under consideration. They assume that bypassing one or more of these devices before the CO_2 discharge point would be possible. They develop a mixed-integer nonlinear programming (MINLP) model that determines which devices to use and the operating condition of each device. Cristóbal et al. (2012a) develop a MINLP for a similar problem where a set of pollution control retrofitting alternatives are considered to be installed in a cap and trade framework.

Santibanez-Gonzalez (2017) compare carbon pricing versus CCS. To that aim, they develop a novel stochastic mixed-integer linear optimization model. Their case study involves cement factories in Brazil. When the price of CO_2 reaches high values such as $60/ton, CCS emerges as a feasible option, but even then the high cost of infrastructure (mostly piping) is found to favor paying taxes instead of installing a carbon capture system in most cases. Wu et al. (2015) develop 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 aims 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 involves China, suggests that it is convenient to capture CO_2 in coal-chemical/liquids/gas and CO_2-enhanced oil recovery (EOR) storage for the early-stage commercialization of CCS.

Arnette (2017) develops 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 is implemented five times, with a maximum of 1.7% of a required 30% decrease in carbon emissions. Hence, they conclude that renewable energy options are more cost-effective means of achieving environmental goals. Ghanbari et al. (2015) work on a 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. Ravi et al. (2016) develop 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 conclude 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, they conclude that pressure swing adsorption is the most efficient CCS technology. Asghari and Shakouri (2014) develop an economic model in which they find the optimum combination of CCS and CCU by considering different storage options. They consider variables such as revenue from CCU, carbon credits, and the distance of storage location to the emission location. Their results show that CCU is the more preferable choice.

A method that is used commonly in CCS-related planning and/or optimization problems is pinch analysis, details of which can be found elsewhere (Roychaudhuri and Bandyopadhyay, 2018). Ooi et al. (2013) develop a novel graphical targeting tool based on pinch analysis in order to address the planning problem of the storage of captured CO_2 from power plants into corresponding reservoirs. They state that the main consideration for the problem is the time of availability of the reservoirs, and their explanation for this reasoning is that reservoirs need to be developed prior to CO_2 storage. Diamante et al. (2014) improve pinch analysis based methodology by simultaneously considering injectivity constraint of every sink as well as time of availability of various sources and sinks. They conclude that the general approach is readily extendable to multi-region systems, where geographic clusters of sources and sinks may exist due to proximity considerations. Valiani et al. (2017) perform the optimization of pre-combustion capture for thermal power plants using pinch analysis. Their efforts resulted in an increase of the efficiency of the power plant by 8%, and a decrease in the fuel consumption by 23%. Tan et al. (2017) developed a P-graph and Monte Carlo simulation approach to carbon management networks (CMN) planning. The first part of their hybrid methodology involves pinch analysis and mathematical programming models based on superstructures; however they suggest that the use of the P-graph framework has the additional advantage of identifying the best solutions, which may then be gauged with Monte Carlo simulation for robustness to probabilistic perturbations. These two steps can thus be combined to ensure that more realistic and practical CMN solutions can be identified for implementation.

Middleton and Bielicki (2009) introduce a comprehensive CCS infrastructure model, SimCCS-scalable (or spatial) infrastructure model for CCS, which determines where and how much CO_2 to capture and store, and where to build pipelines of different sizes to minimize the costs of an integrated CCS system. They develop a mixed-integer linear program (MILP). They demonstrate the first application of SimCCS using 37 CO_2 sources and 14 reservoirs for California to highlight the importance of planning for CCS system by examining the sensitivity of SimCCS to variable CO_2 reduction targets and costs. Stauffer et al. (2014) develop an optimized combination of CCS infrastructure in response to a CO_2 tax on emissions and a CO_2 capture target by using the SimCCS. Another application of SimCCS involves capturing CO_2 from a coal-fired power plant in Midwest, USA and storing the captured CO_2 in depleted oil and gas fields (Middleton et al., 2012a). Several other SimCCS modeling tools (e.g. SimCCSCAP, SimCCSTIME, SimCCSPRICE) are developed to optimize the deployment of CCS infrastructure (Kuby et al., 2009; Keating et al., 2010; Middleton et al., 2012a; b). Each of these models considers the interdependent concerns: deciding where, when and how much CO_2 to capture, transport, inject and store; and how to optimally allocate CO_2 between the sources and reservoirs.

Ellett et al. (2017) develop a new integrated system modeling tool called SimCCUS, which provides supports decision making by integrating application in operations research, geographical information systems, CO_2 capture modeling, pipeline design, and reservoir engineering and geology by extending of SimCCS framework. This tool includes explicit representation of multiple CO_2 usage opportunities in stacked reservoir packages to assess the techno-economic feasibility of CCS projects. SimCCUS consists of three different optimization tools: SimCCUSCAP, SimCCUSTIME, SimCCUSPRICE. The SimCCUS model is applied to a coal power plant in the Illinois Basin, USA in order to evaluate different capture amounts over 30 year and for the optimal solution. They conclude that extending CO_2 utilization for enhanced oil recovery can help drive carbon capture, utilization, and storage technology deployment and expenses of CO_2 mitigation. Middleton and Eccles (2013) explore the impact of variability in electricity generation on the amount of CO_2 captured by a plant, and the carbon price. They focus on the retrofitting gas and coal power plants. They find that the setting a carbon price is sensitive to relatively small changes in the CO_2 value for enhanced oil recovery and the costs for CO_2 transport and storage. Moreover, the cost of CO_2 captured, transport and storage are main drivers in determining the amount of CO_2 captured.

1.3. *Motivation of the study*

In this study, we develop 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 that operate under a cap and trade system. The main differences of our model from the ones in the literature are: (i) it is possible to invest on carbon capture units, storage sites and the pipeline network during any year throughout the planning horizon; (ii) it is possible to sell carbon credits at the emissions trading system (ETS) and generate revenue; and (iii) the decisions about installing carbon capture units, pipeline network, building storage sites, selling carbon to companies for utilization and the amount of carbon traded at ETS are made simultaneously. We implement 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 which the trade-offs between CCS, CCU, and carbon trading have been explored explicitly; and there is no study in which Turkey was analyzed as a case study in that regard. For these reasons we believe that our contribution to the literature is significant.

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, S, that are located in different regions. These power plants, whose carbon emission levels are given by Q_i^s for $i \in S$, operate at 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, $IC(a_i)$, which is a function of the installed carbon capture capacity of the unit, a_i, and an operating cost, $OC(a_{it})$, which depends on the amount of carbon captured at a given year, a_{it} for $i \in S$ and $t \in T$.

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 $t \in T$; and (2) transport the captured carbon to a storage site, R. The storage site is built at a fixed cost of $SC_i(b_i)$, which depends on the capacity of the site, b_i, and the carbon is stored at a variable cost of $VC_i(b_{it})$, which depends on the amount of carbon stored at the site each year, b_{it}, for all $i \in R$ and $t \in T$. If the carbon emission level of the plant is below its cap value, cap_{it}, then they are also entitled to sell the surplus value at the ETS at a price of p_t^E in year $t \in T$. We assume that storage sites may have a limited storage capacity, Q_i^r for $i \in R$, and the amount of carbon to be sold to entities may have an upper bound for each year, Q_i^l for $i \in L$.

We consider a dedicated CO_2 pipeline network through which the captured CO_2 is transported. As indicated by Middleton and Bielicki (2009) pipelines are the only economical way to transport large volumes of CO_2. On this pipeline network, besides source (power plants) and sink (storage sites and utilization points) nodes, there will be some intermediate nodes where different pipelines intersect. This structure helps the construction of the pipeline network benefit from economies of scale. We represent all nodes on the network, including source, sink and intermediate nodes, as a set N. The pipeline can have various diameters from a set of D. The transportation cost over the pipeline has a fixed, F_{ijdt}^p, and a variable parts, V_{ij}^p, which depend on the diameter of the pipeline $d \in D$, the construction year $t \in T$, and the distance between nodes $i \in N$ and $j \in N_i$. We represent the adjacent nodes of node i as set N_i. We provide all parameters used in the model with their symbols in Table 1.

For the problem defined, we have different decisions to make each year: (*i*) either install a carbon capture unit, $s_{it} = 1$, or not, $s_{it} = 0$ at $i \in S$ and $t \in T$; (*ii*) the capacity of the carbon capture unit, a_i for $i \in S$, if decided to be built, and the amount of carbon captured at a unit, a_{it} for $i \in S$ and $t \in T$; (*iii*) either to construct the edges on the carbon pipeline network at a given diameter, $y_{ijdt} = 1$, or not, $y_{ijdt} = 0$ for $i \in N$, $j \in N_i, d \in D$ and $t \in T$; (*iv*) amount of carbon transported from node $i \in N$ to node $j \in N_i$ over the pipeline network in year $t \in T$, x_{ijt}; (*v*) either to open a storage site at a node, $r_{it} = 1$, or not, $r_{it} = 0$, and the amount of carbon sent to this site, b_{it},

Table 1
Nomenclature.

Symbol	Description
T, S, R	set of planning years, power plants (sources), storage sites (reservoirs)
L	set of entities that are willing to utilize the captured carbon
N	set of nodes on the pipeline network, including sets S, R, and L
N_i	set of nodes adjacent to node $i \in N$ on the pipeline network
D	set of possible diameter values for the pipeline network
Q_i^s	annual carbon production capacity of a source node $i \in S$ (ton/year)
Q_i^r	total carbon storage capacity of site node $i \in R$ (ton)
Q_i^l	annual carbon utilization amount that can be sent to entity $i \in L$
Q_{ijd}^p	carbon capacity of a pipeline with diameter $d \in D$ built between nodes $i \in N$ and $j \in N$ (ton/year)
cap_{it}	cap value on the emissions level of power plant $i \in I$ at year $t \in T$ (ton/year)
$IC(a_i)$	installation cost of a carbon capture unit with carbon capture capacity of a_i ($)
$OC(a_{it})$	operating cost of a carbon capture unit with annual capacity of a_{it} ($)
$SC(b_i)$	fixed cost of building a storage site with a total capacity of b_i ($)
$VC(b_{it})$	variable cost of storing annually b_{it} amount of carbon ($)
F_{ijdt}^p	fixed cost of building a pipeline with diameter $d \in D$ between nodes $i \in N$ and $j \in N$ in year $t \in T$ ($)
V_{ij}^p	variable cost of sending a unit carbon between nodes $i \in N$ and $j \in N$ ($/ton)
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 ETS in year $t \in T$ ($/ton)

for $i\in R$ and $t\in T$; (vi) the amount of carbon sent to a company for utilization, c_{it} for $i\in L$ and $t\in T$; and finally (vii) the amount of carbon that will be either bought or sold at the ETS, e_{it} for $i\in S$ and $t\in T$. All these symbols with their definitions are provided in Table 2.

2.2. Mathematical model

We develop a mixed-integer programming model that aims to minimize the overall cost of the carbon capture structure considered for a set of thermal power plants that operate under a cap and trade system. We next provide the equations used in the optimization model.

$$\begin{aligned} z = \sum_{t\in T}\frac{1}{(1+r)^t}\Bigg[&\sum_{i\in S}(IC(a_i)s_{it}+OC(a_{it}))+\sum_{i\in R}(SC_i(b_i)r_{it}\\ &+VC_i(b_{it}))+\sum_{i\in N}\sum_{j\in N_i}\left(\sum_{d\in D}F^p_{ijdt}y_{ijdt}+V^p_{ij}x_{ijt}\right)\\ &+\sum_{i\in S}p^E_t e_{it}-\sum_{i\in L}p^C_t c_{it}\Bigg]\end{aligned} \tag{1}$$

Equation (1) calculates the net present value of (i) the installation, $IC(a_i)$, and operating cost, $OC(a_{it})$, of the carbon capture units depending on the amount of carbon captured each year, a_{it}, and the capacity of the carbon capture units, a_i, if they are installed, i.e., $s_{it} = 1$, (ii) the fixed, $SC_i(b_i)$, and variable, $VC_i(b_{it})$, storage cost of the carbon captured depending on the amount of carbon stored each year, b_{it}, and the capacity of the storage sites, b_i, if storage sites are open, i.e., $r_{it} = 1$, (iii) the fixed, F^p_{ijdt}, and variable, V^p_{ij}, transportation cost of carbon over the pipeline network that includes transportation from sources to storage sites and to entities for utilization depending on the amount of carbon transported, x_{ijt}, if corresponding pipelines are built, i.e., $y_{ijtd} = 1$, (iv) the cost (or revenue), p^E_t, that results from a transaction, e_{it}, at the ETS, and finally (v) the negative revenue, p^C_t, of selling carbon, c_{it}, to entities for utilization. Note that the fixed investment cost, $IC(a_i)$, and the operating cost, $OC(a_{it})$ of CCS units, and storage costs, $SC(b_i)$ and $VC(b_{it})$, can be any type of function depending on the carbon capture capacity of the unit, the amount of carbon captured at the unit at a time period, the capacity of the storage unit and the amount of carbon stored at a time period, respectively.

Table 2
Decision Variables.

Symbol	Description
a_{it}	amount of carbon captured in node $i\in S$ in year $t\in T$ (ton)
b_{it}	amount of carbon stored in node $i\in R$ in year $t\in T$ (ton)
c_{it}	amount of carbon sold to node $i\in L$ in year $t\in T$ (ton)
a_i	capacity of a carbon capture unit built in node $i\in S$ (ton)
b_i	total amount of carbon stored in node $i\in R$ (ton)
x_{ijt}	amount of carbon sent from node $i\in N$ to $j\in N$ in year $t\in T$ (ton)
e_{it}	amount of carbon traded at the ETS in year t that is captured in node i (ton)
s_{it}	$= 1$, if a carbon capture unit is installed at node $i\in S$ in year $t\in T$; $= 0$, otherwise
r_{it}	$= 1$, if a reservoir is built in node $i\in R$; $= 0$, otherwise
y_{ijdt}	$= 1$, if a pipeline with diameter $d\in D$ is built from node $i\in N$ to node $j\in N$; $= 0$, otherwise

$$a_{it} = \sum_{j\in N_i} x_{ijt}, \quad \forall i\in S, t\in T; \tag{2}$$

Equation (2) calculates the amount of carbon captured, a_{it}, at a source node $i\in S$ in each year $t\in T$. We use this auxiliary variable a_{it} to keep track of the amount of carbon captured at each source node at each year.

$$a_i \geq a_{it}, \quad \forall i\in S, t\in T; \tag{3}$$

Equation (3) determines the capacity level of the carbon capture unit, a_i, at each source node $i\in S$ if it is installed. We use auxiliary variable a_{it} for this purpose. Since a_i will be greater than or equal to all a_{it} and the objective is a minimization function, in the optimal solution the capacity level, a_i, will be equal to the maximum amount of carbon captured over the planning horizon, i.e. $a_i = \max_{t\in T}\left\{\sum_{j\in N_i} x_{ijt}\right\}$.

$$b_{it} = \sum_{j\in N_i} x_{jit}, \quad \forall i\in R, t\in T; \tag{4}$$

Equation (4) calculates the amount of carbon sent to each storage site $i\in R$ in each year $t\in T$. We use this auxiliary variable b_{it} to keep track of the amount of carbon stored at each sink node (storage site) at each year.

$$b_i = \sum_{t\in T} b_{it}, \quad \forall i\in R; \tag{5}$$

Equation (5) gives the total amount of carbon stored, b_i, at each storage site $i\in R$, throughout the planning horizon. We simply sum up the amount of carbon sent to each storage site every year, and then sum that value up over the planning horizon.

$$c_{it} = \sum_{j\in N_i} x_{jit}, \quad \forall i\in L, t\in T; \tag{6}$$

Equation (6) calculates the amount of carbon sold, c_{it}, to each utilization company $i\in L$, at each year $t\in T$. For that purpose we sum up the amount of carbon transported to each company for the respective year.

$$x_{ijt} \leq \sum_{d\in D} Q^{p,max}_{ijd}\left(\sum_{t'\leq t} y_{ijdt'}\right), \quad \forall i\in N, j\in N_i, t\in T; \tag{7}$$

$$x_{ijt} \geq \sum_{d\in D} Q^{p,min}_{ijd}\left(\sum_{t'\leq t} y_{ijdt'}\right), \quad \forall i\in N, j\in N_i, t\in T; \tag{8}$$

The amount of carbon sent through each section of the pipeline must be between the corresponding section's maximum, $Q^{p,max}_{ijd}$, and minimum, $Q^{p,min}_{ijd}$, capacity levels, which depend on the diameter, $d\in D$, of the pipeline constructed. Equations (7) and (8) ensure these limits if a pipeline is installed, i.e. $y_{ijdt} = 1$. Note that the decision on installing a pipeline and a carbon capture unit are made simultaneously at any time period during the planning horizon.

$$\sum_{j\in N_i} x_{ijt} - \sum_{j\in N_{i\notin R}} x_{jit} - a_{it} + b_{it} + c_{it} = 0, \quad \forall i\in N, t\in T; \tag{9}$$

For each node, $i\in N$, on the network, we need to make sure that the amount of inflow, $\sum_{j\in N_i} x_{ijt} + b_{it} + c_{it}$, and outflow, $\sum_{j\in N_{i\notin R}} x_{jit} + a_{it}$, are balanced. Equation (9) ensures that this balance holds. Note that only one of a_{it}, b_{it}, and c_{it} can be positive at the same time for a node: If the node is a source node, then only a_{it} can be positive, i.e., $b_{it} = c_{it} = 0$. If the node is a sink node, then only b_{it} can be positive, i.e., $a_{it} = c_{it} = 0$. Finally, if the node represents a utilization company, then only c_{it} can be positive, $a_{it} = b_{it} = 0$.

$$a_{it} \le Q_i^s \sum_{t' \le t} s_{it'}, \quad \forall i \in S, t \in T; \tag{10}$$

Equation (10) ensures that the amount of carbon, a_{it}, sent out of a source node $i \in S$, cannot exceed the amount of carbon produced at that node, Q_i^s. We multiply this limit with the summation of binary variables, s_{it}, over a time horizon that starts from the beginning of the planning horizon, and stops at the current year. By this summation, we make sure that it is not possible to capture carbon at any year if a CCS is not installed in a year during previous time period.

$$b_i \le Q_i^r \sum_{t' \le t} r_{it'}, \quad \forall j \in R, t \in T; \tag{11}$$

Equation (11) ensures that the amount of carbon, b_i, sent to a storage site $i \in R$ does not exceed its capacity, Q_i^r. Similar to the discussion above, by summing up the binary variable r_{it} over the previous years and multiplying it with the capacity of the storage site, we make sure that no carbon is stored if that storage site is not open.

$$c_{it} \le Q_i^l, \quad \forall i \in L, t \in T; \tag{12}$$

Equation (12) ensures that the amount of carbon, c_{it}, sent to an entity for utilization does not exceed its annual limit, Q_i^l.

$$a_{it} + e_{it} = Q_i^s - cap_{it}, \quad \forall i \in S, t \in T; \tag{13}$$

Equation (13) ensures that the total amount of carbon captured at a source node, a_{it}, and the amount of carbon traded at the ETS, e_{it}, is equal to the total emission level of the power plant, Q_i^s, less the cap value assigned to the company at a given year, cap_{it}. Note that e_{it} is defined as an unrestricted variable; and if the company is entitled to sell the amount of carbon that is below the cap value, e_{it} will take a negative value. On the other hand, if the emission level of the company is above its cap value, then e_{it} will take a positive value. In Equation (1), when e_{it} is negative, the company earns revenue as a result of selling the surplus value at the ETS.

$$\sum_{t \in T} s_{it} \le 1, \quad \forall i \in S; \tag{14}$$

$$\sum_{t \in T} r_{it} \le 1, \quad \forall i \in R; \tag{15}$$

A carbon capture unit can be installed at a power plant only once during the planning period, and the same is true for storage sites. These are provided with Equations (14) and (15).

$$\sum_{d \in D} \sum_{t \in T} y_{ijdt} \le 1, \quad \forall i \in N, j \in N_i; \tag{16}$$

Equation (16) makes sure that only one size of a pipeline can be constructed at an edge of a network, and this can occur only once during the planning horizon.

Then, the optimization model for the problem that we study can be written as follows:

Min (1)

Subject to (2)–(16)

$$s_{it}, b_{it}, y_{ijtd} \in \{0,1\}, \quad \forall i \in N, j \in N_i, d \in D, t \in T; \tag{17}$$

$$a_i, a_{it}, b_i, b_{it}, c_{it}, x_{ijt} \ge 0, \quad \forall i \in N, j \in N_i, t \in T, \tag{18}$$

where (17)–(18) are the binary and nonnegativity restrictions over the decision variables.

3. Case study

We consider two power plants located in Soma (west of Turkey) and Afsin (southeast of Turkey). They are indicated as stars in Fig. 2. These power plants are lignite-fired power plants with installed capacities of 1000 MW and 1800 MW, respectively. Both plants operate with a capacity factor of 85%. Although there is currently no operational ETS in operation in Turkey, the Directorate General of Environmental Management under the Ministry of Environment and Urbanization is currently investigating an ETS 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) transport CO_2 to storage sites, which are Mediterranean Sea (under deep sea level 50 km away from the shoreline) and Salt Lake (they are marked with hexagons on the map given in Fig. 2); and (2) sell the carbon captured to the oil companies located in Mosoul, Iraq, to be used in EOR (marked as a square on the map in Fig. 2). According to the Turkish Renewable Energy General Directorate, the only suitable location for EOR in Turkey is West Raman, however the resource capacity is limited (Tubitak Kamag 106G110 (2009)) and for this reason we preferred to choose Mosoul as it is the closest place to Turkey that has major oil production sites. The same study also revealed that all known CO_2 storage sites in Turkey have limited capacity, and they are only suitable for the storage of CO_2 emitted by small and medium scale industrial enterprises. They also added that underwater storage (in Mediterranean Sea) should be investigated further as a possible means of large scale CO_2 storage. The reason we selected Salt Lake as an on-shore CO_2 location is that there is a real life project on storing natural gas in that region (Tuz Golu, 2017, 0000), which means that geologically Salt Lake seems to be suitable for underground gas storage.

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, a_i, is given as follows:

$$IC(a_i) = 640,800,000 \left(\frac{a_i}{\max_{t \in T}\{m_{it}\}} \right)^{0.6} + 31.3 a_i \tag{19}$$

where 640,800,000 is the capital investment in USD 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 0.6^{th} power of the ratio of the capacities of the actual equipment and the reference equipment (Peters et al., 1968). We include the CO_2 purification & compression cost as a linear function of a_i, i.e., $31.3a_i$, based on the data provided in Kolster et al. (2017). In accordance with the data in the same paper, we take the operating cost of the unit as a linear function of the amount of carbon captured in each year, which is $OC(a_{it}) = 21.6 a_{it}$.

We calculate the pipeline cost by using the following

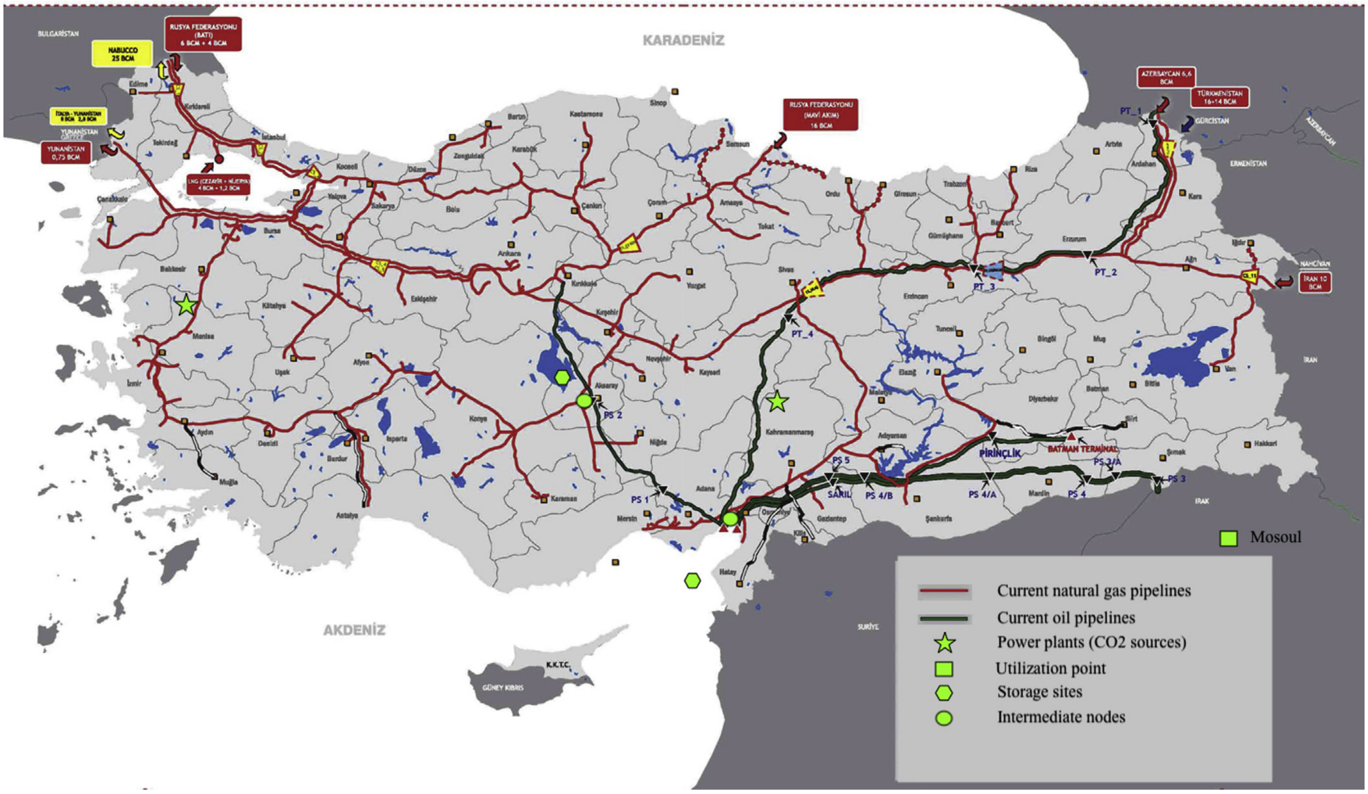


Fig. 2. Turkey's map that show source, sink and intermediate nodes, and current natural gas and oil pipeline system (www.botas.gov.tr).

methodology: we first obtain the piping diameter, which is the main pipe-design parameter, according to the following equation (Serpa et al., 2011).

$$D^5 = \frac{32 f_F Q_m^2}{\rho \pi^2 (\Delta p / L)}, \tag{20}$$

where D is the pipe diameter in meters, f_F is the Darcy friction factor, Q_m is the flow rate of CO_2 (kg/s), ρ is the density of CO_2 (app. 200 kg/m^3 at an average pressure of 10 MPa and average temperature of 10 °C based on ideal gas law), Δp is the pressure drop (Pa) across the pipe and L is the pipeline length (m). By using the graphical version of this equation from the same reference, we obtain a relationship between CO_2 flow rate and pipe diameter. However, pipe diameter is not a continuous function as pipes are only manufactured with certain diameter values. Therefore, we use data provided by Middleton and Bielicki (2009) to obtain possible pipe diameter values for various flow rate ranges; and then we use the following equation to obtain the initial cost of the piping system:

$$F_{ijdt} = \pi \times \rho_{steel} \times h(D+h) \times d_{ij} \times 1000, \tag{21}$$

where $\rho_{steel} = 7850$ kg/m^3, h is the thickness of the pipe used, which is taken as 0.008 meter, D is the diameter of the pipe, and d_{ij} is the distance between nodes i and j. We take possible pipe diameters as 4, 6, 8, 12, 16, 20, 24 and 30 inches as given in Middleton and Bielicki (2009). We also used the minimum and maximum transportation capacities of each size of pipe provided in the same paper. We provide the distances between each node given on the map (Fig. 2) in Table 3. We take the annual variable cost of transporting CO_2 over the pipeline fixed at the 4% of its fixed cost (Kang et al., 2015). We take the storage cost as a linear function of the amount of carbon stored where unit cost is $10 based on the analysis given in Zero Emission Platform (2011). For this case study, we assume that the storage sites' fixed costs are paid by the government, hence they are equal to zero.

Table 3
Distances between nodes (km).

i–*j*	Distance	*i*–*j*	Distance
1–2	950	2–3	90
2–4	300	4–5	50
6–4	220	4–7	820

Finally, based on the data obtained from Tubitak Kamag 106G110 (2009), the maximum CO_2 storage capacity is determined as 3 billion m^3 for Salt Lake (the total capacity is reported as 5.4 billion m^3, however 1 billion m^3 of natural gas storage is in the planning horizon for 2020 and the remaining 1.4 billion m^3 is assumed as the buffer volume between the two gases). We assume that there is no capacity limit for the site planned to be built under Mediterranean Sea.

4. Results

We implemented the model on General Algebraic Modeling System (GAMS) on a machine with Intel Xeon 2.27 GHz CPU, 24 GB RAM and Windows 2008 Server R2 operating system. As explained in the previous section, the objective function includes a nonlinear term, which is the installation cost of carbon capture units. Therefore, we first select BARON (Sahinidis, 2015), which guarantees to find global optimal solution for MINLPs, as the solver. However, the solver experienced numerical difficulties and stopped at local optimal solutions for different data sets. Then, we analyzed the model and observed that the objective function is a concave function of the capacity of the carbon capture unit, and the constraint set is linear forming a polyhedron. This requires the optimal solution to be found in one of the extreme points of the feasible region. We analyzed the model's constraints and realize that the upper and lower capacities over pipes based on their discrete diameter sizes, as well as the capacity limits over the source and sink nodes and nonnegativity restrictions constitute the extreme points. Hence, we approximated the nonlinear part of the objective function with a piecewise linear function by using the pipes', sources' and sinks' capacity limits as the break points. We provide the corresponding linear approximation functions in Fig. 3. We solved the resulting MILP using Cplex 12.8 (Cplex, 2017), which guarantees to find an optimal solution. The model is solved to optimality within a few seconds.

We apply sensitivity analysis over the carbon price and the maximum limit over the utilizable carbon as these factors are the ones that affect the optimal decision most compared to other parameters.

We take two different prices for utilization, $p^C = \$5$ and \$10, as they are the closest values to real life prices (Naims, 2016); and four prices for the emissions trading system: $p^E = \$15$, \$20, \$25 and \$30 as lower values do not impose any carbon mitigation policies to be adopted. We increase the carbon price value at ETS, p^E, 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 change the limit over the possible amount of carbon that can be utilized, Q^l, on the interval 0, for which it is not possible to sell for utilization, and 22.5 Mtons, for which it is possible to sell all carbon that are captured at both plants, in 2.5 Mtons increments. 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.

Fig. 4 provides the optimal decisions for each scenario. For every scenario related to carbon utilization limit, Q^l, (x-axis), we provide three values: the amount of carbon captured at Soma plant (legend Soma) and at Afsin plant (legend Afsin), and the amount of carbon stored at Mediterranean Sea (legend Stored). According to our computational analysis, Salt Lake is never chosen as an option for a storage site. The main reason is the structure of the pipeline used. As shown in the map provided in Fig. 2, if the carbon captured at Soma plant is sold for utilization, then the pipeline that transports the carbon captured must pass through the node that is at the shoreline of Mediterranean Sea. After the carbon is transported to this node, it is always less costly to use Mediterranean Sea as a storage site as it is close to this node and it does not have any capacity restriction. Therefore, we do not include Salt Lake as a storage site in Fig. 4. Moreover, if it is optimal to capture some amount of carbon, it is always optimal to sell it for utilization at its maximum limit value. When $p^C = \$5$ and $p^E = \$15$, the optimal solution restricts us to not construct any pipeline at all for all scenarios. For the case with $p^C = \$10$ and $p^E = \$30$, the optimal solution is to capture all carbon at both plants, transport them to the utilization point at its maximum limit and store the remaining under the Mediterranean Sea. Since the optimal solution does not change for different values of Q^l, we do not provide these solutions in Fig. 4.

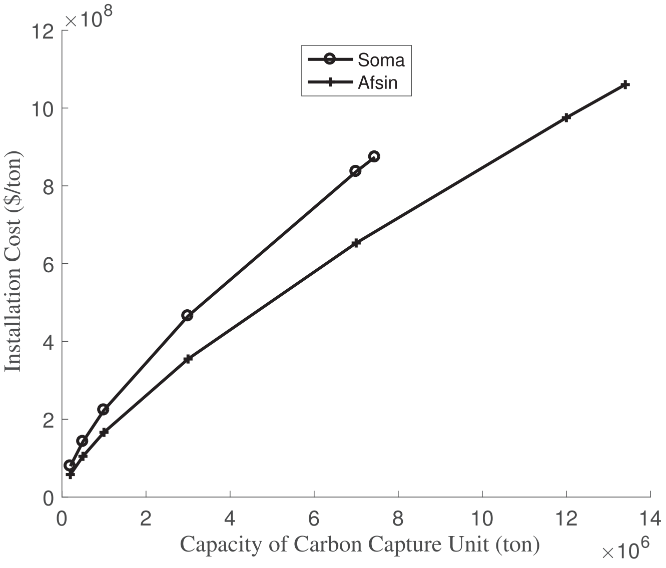


Fig. 3. Approximate Piecewise Linear Function of Installation Cost, $IC(a_i)$, at Carbon Transportation Limits of Different Sizes of Pipes.

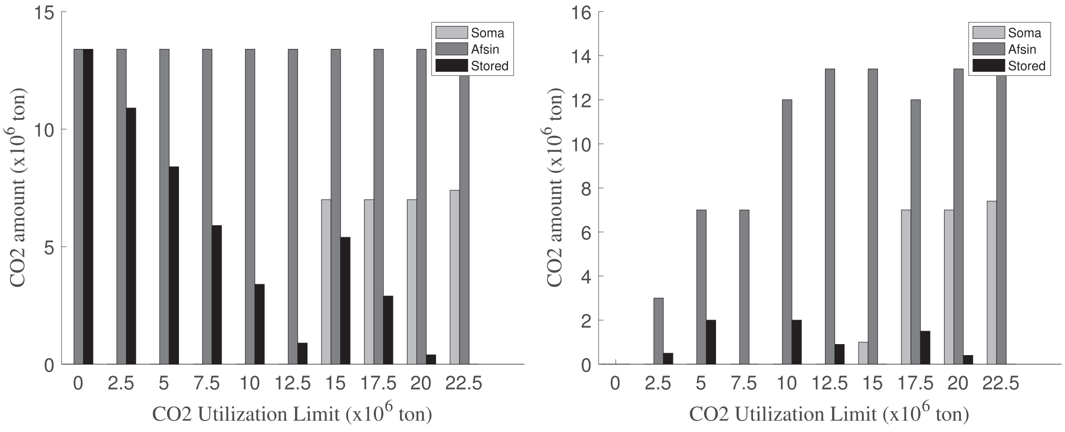
We observe that when carbon utilization is not an option, i.e., $Q_l = 0$, then it is optimal to capture carbon produced at Afsin plant only when $p^E = \$30$ (see Fig. 4a). For all other cases, it is optimal not to install any carbon capture unit for both plants at all. On the other extreme, when there is practically no limit over the amount of carbon that can be utilized, i.e., $Q_l = 22.5$ Mtons, it is optimal to install carbon capture units for both power plants at their maximum capacities except two cases when $p^E = \$20$ and $p^C = \$5$ (see Fig. 4e) and when $p^E = \$15$ and $p^C = \$10$ (see Fig. 4f). For these cases, it is optimal to install a capture unit at Afsin at its full capacity and none for Soma plant.

The highest capacity of carbon capture unit installations are realized when the carbon price at ETS is at highest value, $p^E = \$30$. This is expected because not capturing any carbon would lead to high costs from carbon trading; and it is possible to make money by capturing carbon and selling credits at ETS. For higher utilization limits, the system's overall cost is negative, meaning that it is possible to make profit throughout the planning horizon by installing carbon capture units. Moreover, when $p^E = \$25$ and $p^C = \$10$ and the utilization limit is higher than 15 Mtons, the system makes profit by installing carbon capture units at both plants.

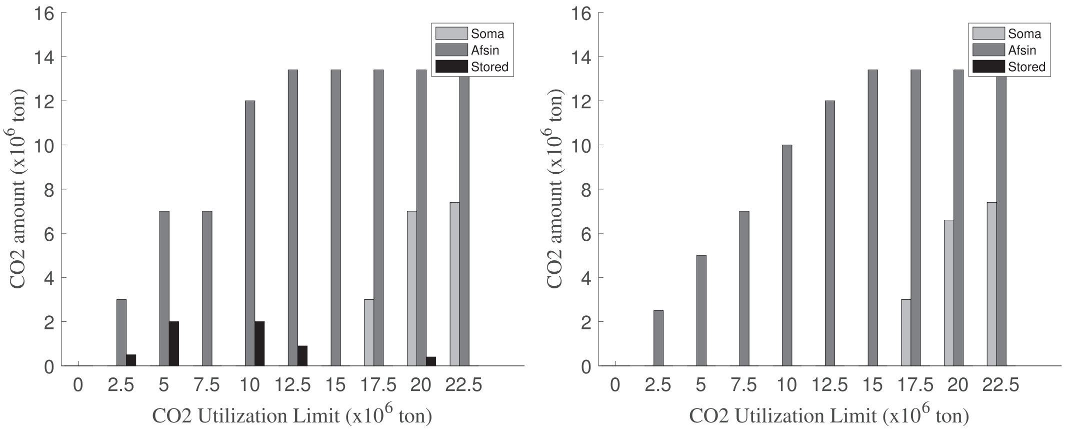
Another significant outcome is regarding the effect of the discrete pipe diameters, and hence, discrete costs and lower and upper limits. For example, although it is possible to sell carbon for utilization, the model installs a lower capacity capture unit because of the pipe's upper limit, see Fig. 4e where $Q^l = 12.5$ Mtons. A similar pattern exists for Soma plant, where instead of installing a capture unit at its highest possible capacity, i.e. 7.4 Mtons, the model invest in a smaller amount of unit (7 Mtons) in order not to pay for a pipeline that has higher cost (see Fig. 4a, b, c, and d, with $Q^l = 20$ Mtons). Note that the upper limit for a pipe with diameter 16 inches is 7 Mtons/year and it is not worth installing a pipe with higher diameter just to transport marginally increased amount of carbon at a high cost.

We observe interesting trends for carbon prices of \$30 and \$5 for trading and utilization, respectively. When the utilization limit is \$15 Mtons/year, it is optimal to wait until year 5 to invest on a carbon capture unit for Soma plant. Moreover, the timing of installing a pipeline through Mediterranean Sea changes based on the limit over the utilization amount (between year 1 and 7). For the same case, when it is practically impossible to sell carbon for utilization, it is optimal to install a capture unit at Afsin in year 7.

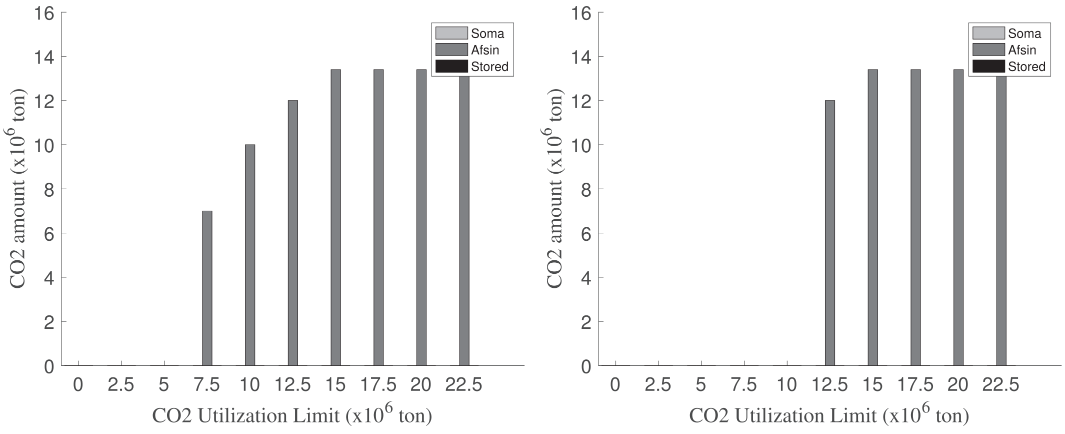
These results agree with earlier studies in which it was stated that below a certain carbon price, carbon capture of any sort



(a) $p^E = 30,\ p^C = 5$ (b) $p^E = 25,\ p^C = 10$



(c) $p^E = 25,\ p^C = 5$ (d) $p^E = 20,\ p^C = 10$



(e) $p^E = 20,\ p^C = 5$ (f) $p^E = 15,\ p^C = 10$

Fig. 4. Optimal carbon capture, storage and utilization decisions for various scenarios.

becomes infeasible (Santibanez-Gonzalez, 2017; Arnette, 2017), and carbon trading emerges as the more feasible option (Üçtuğ et al., 2014).

We provide the optimal network structure in Fig. 5 for the scenario given in Fig. 4c with $Q^l = 20$ Mtons/year.

5. 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 and pipeline cost for transporting carbon less the revenue that would be obtained by

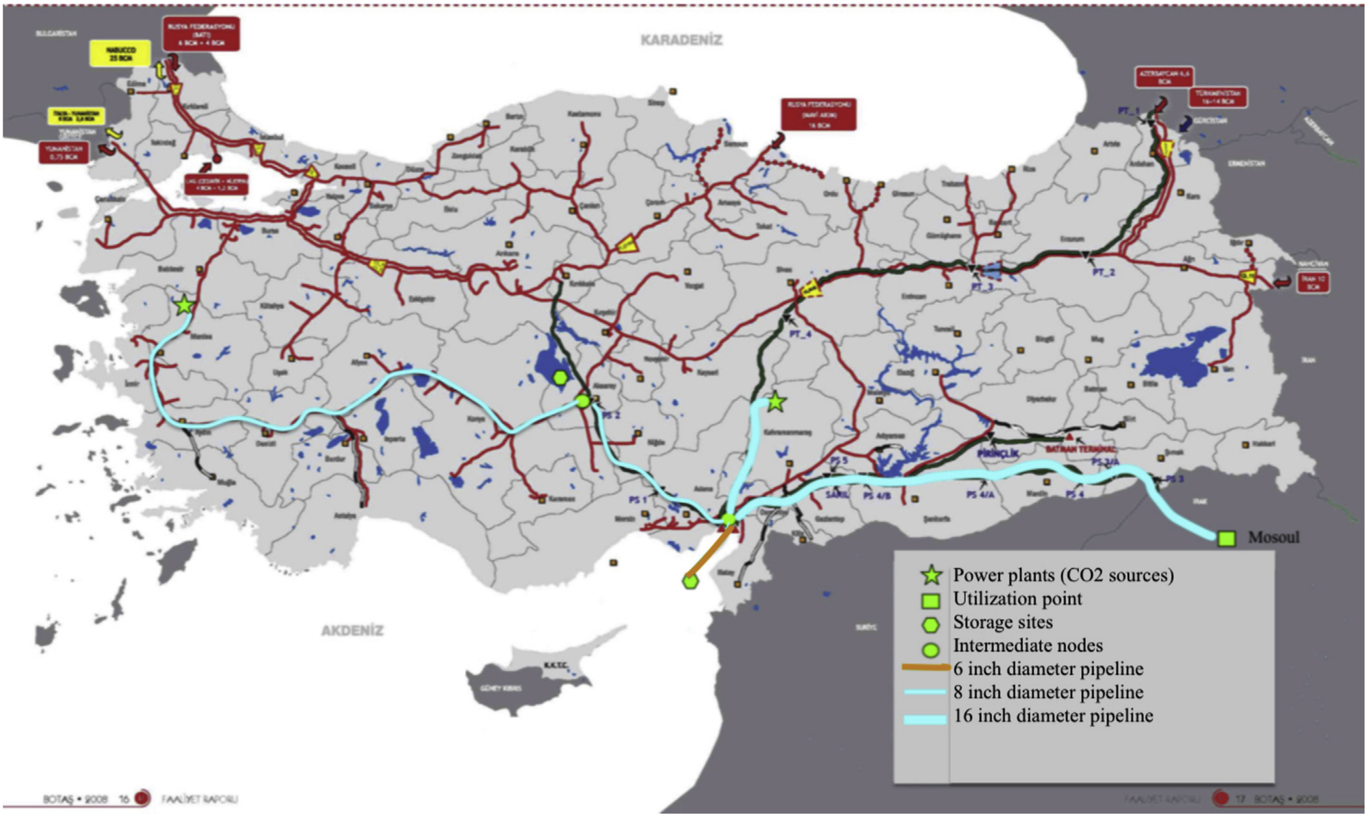


Fig. 5. Optimal transportation network for the scenario with $p^E = \$30$, $p^C = \$5$ and $Q^I = 15 \times 10^6$ tons.

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 at ETS, storage and transportation costs, the limits over the pipeline network, 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 Afsin (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 Afsin 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 Afsin 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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