IICEC SABANCI UNIVERSITY ISTANBUL INTERNATIONAL CENTER FOR ENERGY AND CLIMATE

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IICEC ENERGY AND CLIMATE RESEARCH PAPER

Carbon Capture, Utilization and Storage in the Context of Turkish Energy Market

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1. Summary

Combusting fossil fuel is the conventional approach to initiate a set of chemical reactions, which releases stored energy as heat, carbon dioxide (CO_2), nitrogen oxides (NO_x) and other pollutants. Among all fossil fuels, coal, used in nearly 40% of the world's power production, when combusted, releases several other harmful pollutants such as sulfur dioxide (SO_2), mercury, particulate matter, volatile organic compounds (VOCs), lead and arsenic.[i] In modern coal power plants, as required by regulations that are common in the OECD, these harmful chemicals and heavy metals must be removed from the flue gas using various pollution control technologies. However, these regulations do not govern the emissions of CO_2 since CO_2 does not contribute to local pollution and happens to be the inevitable and most stable oxidation product of any hydrocarbon.

It is well known that the energy sector is contributing to a significant rise in the concentration of atmospheric greenhouse gases (GHGs) that cause more heat to be absorbed by the Earth than is radiated back out into space. It is estimated by the Intergovernmental Panel on Climate Change (IPCC) that the concentration of GHGs is going to reach dangerous levels if future GHG emissions from the energy sector are not significantly reduced.[ii] Several models, for example, the International Energy Agency's Energy Technology Perspectives model, show that the energy sector cannot achieve a safe level of emissions unless coal use is almost entirely curtained or if CO_2 is separated from the coal power plant instead of being emitted into the atmosphere and the CO_2 stored in deep reservoirs or otherwise used.[iii]

Since Turkey has huge domestic coal reserves, coal power is a source of electricity that can contribute to Turkey's energy security. While Turkey's emissions of CO_2 are small compared to those of other developing countries such as China and India, the rest of Europe or the United States, international agreements like the Paris Accord aim to achieve a world-wide collective effort from all countries. Consequently, carbon capture, utilization, and storage (CCUS) could be important to Turkey given Turkey's large coal reserves and desire to use domestic energy resources as a source of energy security and to reduce its energy import bill. CCUS is the set of methods and technologies that removes CO_2 from the emissions and prevents them from leaking into the atmosphere. In this study, we focus on the application of aqueous Monoethanolamine (MEA) scrubbing method as a well-proven carbon capture (CC) technology on the Turkish coal-fired power plants. We investigate the economic and environmental impacts of MEA scrubbing technology in the context of the Turkish energy market. For the sake of completeness, we consider nine storage candidates, one domestic CO_2-enhanced oil recovery in Batman, and an emissions trading market. A mixed-integer nonlinear programming model (MINLP) is developed based on regulations and techno-economic factors. Equilibrium solutions of the proposed model are obtained regarding independent and coordinated actions of power plants. Finally, managerial insights are proposed.

2. Introduction

As noted above, CO_2 traps heat and creates a phenomenon, the so-called greenhouse effect. To compare the heat-trapping power of greenhouse gasses (GHGs) in the atmosphere, scientists use a relative measure called global warming potential (GWP). By this measure, the greenhouse effects of GHGs are analyzed with those of CO_2 as the reference gas. Table 2.1, which is adopted form Gillenwater et al., (2002)[iv], displays GWP values of multiple gasses.

Table 2.1: Global warming potential and the atmospheric lifetime (years) of different gasses.

Gas	Atmospheric Lifetime	100-year GWP	20-year GWP	500-year GWP
Carbon dioxide (CO_2)	50 - 200	1	1	1
Methane (CH_4)	12 ± 3	21	56	6.5
Nitrous oxide (N_2O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400

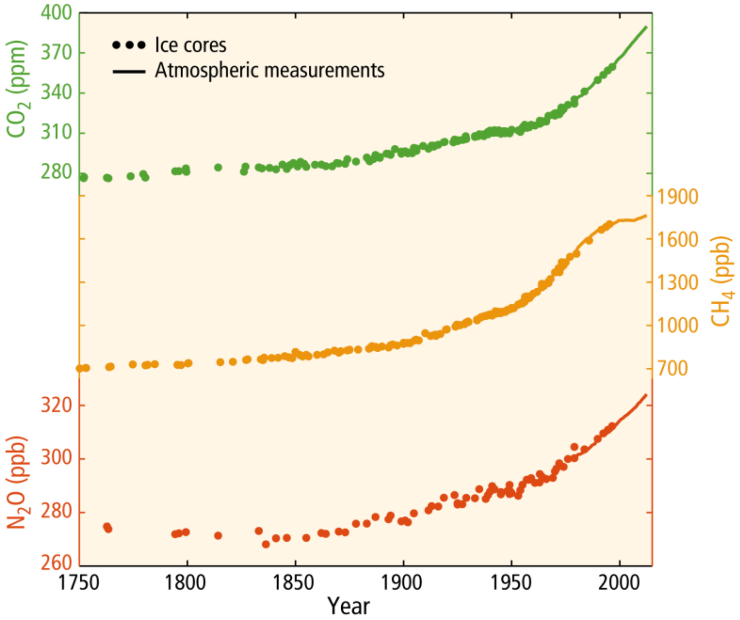
While the GWP value of CO_2 is much lower than other gasses in Table 2.1, it is a prolific gas emitted from the combustion of fossil fuels, emitted in far greater volume than the others GHGs. Being relatively stable, it also has a longer atmospheric lifetime than the others. Consequently, the atmospheric concentration of GHGs is increasing (Figure 2.1). Also, as mentioned above, IPCC climate studies have shown that there is a significant likelihood that these emissions will cause harmful climate change, including increased drought, and with it reductions in food production, sea-level rise and many other adverse consequences.[v]

Natural CO_2 emissions in the atmosphere from volcanic activities, decomposition, and ocean release and respiration have been balanced for millions of years through carbon sequestration. For instance, in terrestrial sequestration (TS), plants absorb CO_2 from the atmosphere and through photosynthesis transform CO_2 into glucose and oxygen:

$$12\ H_2O + 6\ CO_2 \rightarrow 6\ H_2O + C_6H_{12}O_6 + 6\ O_2$$

Figure 2.1: The average concentration of CO_2, N_2O and CH_4 in the atmosphere

(Source: Figure 1.3[vi])



Finally, plants safeguard absorbed carbon in the root, stem, and soil. However, the current CO_2 concentration in the atmosphere, due to industrial revolution and the demand for energy, is exceeding vegetation TS capacity. Thus, researchers are trying to emulate these natural processes for carbon absorption with machines that could replicate photosynthesis in plants more efficiently[vii,viii,ix].

Fossil fuels are being extracted from carbon sinks in the form of coal, oil and natural gas. Nonetheless, coal is a chemically complicated fuel and when combusted, releases numerous harmful pollutants that directly affect health as it is shown in Table 2.2. Coal mining also releases another GHG, methane (CH_4)[x].

Table 2.2: Comparing pollutants in natural gas, oil and coal
(lbs/billion BTU of energy input, Source: EIA - Natural gas Issues & Trends[xi])

Pollutant	Natural gas	Oil	Coal
Carbon dioxide	117,000	164,000	208,000
Carbon monoxide	40	33	208
Nitrogen oxides	92	448	457
Sulphur dioxide	1	1122	2591
Particulates	7	84	2744
Mercury	0	0.007	0.016

Turkey has huge lignite reserves and a number of hard coal[1] deposits. Unfortunately, Turkish lignite has a low calorific value (CV) and high sulphur, dust, and other contents. Turkish hard coal is also of low grade but cokeable or semi-cokeable quality. Most of the lignite is extracted from low-

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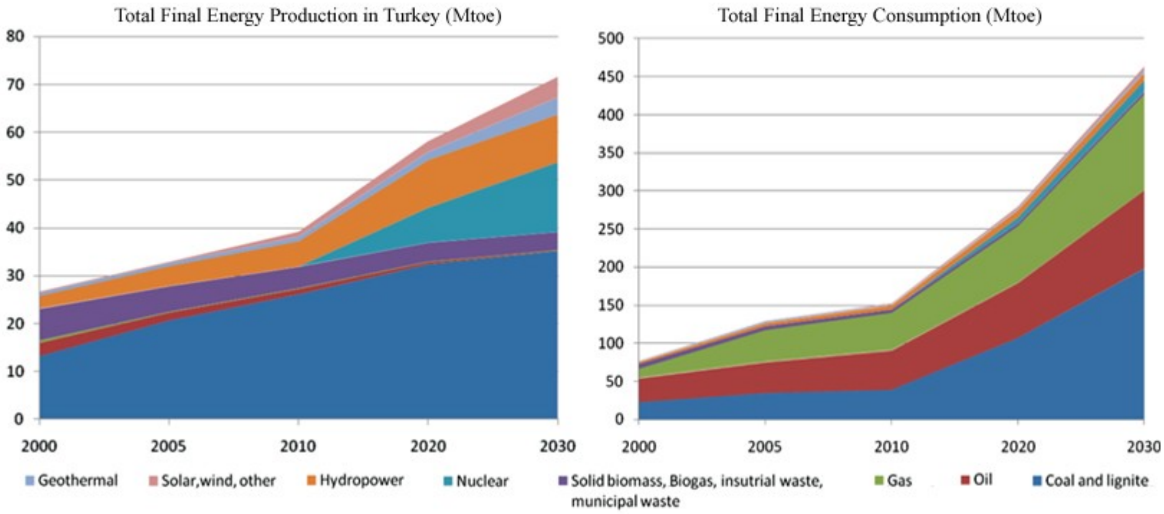
[1] Hard coal is mined only in the Zonguldak Basin near black sea coast

cost opencast mines. There are also asphaltite reserves of 82 million tons in the Şırnak and Silopi areas[xii].

The current energy strategy of Turkey is backing the total utilization of domestic lignite and hard coal for energy generation purposes. According to projections, conducted by the Ministry of Energy and Natural Resources of Turkey (MENR), coal share in the energy mix is expected to rise from 24% in 2004 to 36% by 2020[xiii,xiv]. Figure 2.2 depicts projections of fuel/energy use in the Turkish power sector (left graph) and Turkish energy consumption in all sectors (right graph) through 2030.

Figure 2.2: MENR projections until 2030.



Moreover, Turkish coal-fired power plants are utilizing old technologies[2,xv], which means they are less efficient and produce more CO_2 per GWh than their European counterparts[3,xvi]. In 2014, German coal-fired power plants release only 64.35% CO_2 per GWh compare to Turkish power plants.

In order to reduce CO_2 emissions from coal power plants, several solutions may come into mind. The first solution is to utilize new technologies in future coal-burning power stations. According to the Electric Power Research Institute (EPRI), an advanced ultra-supercritical pulverized coal (A-USC) power plant can enhance the performance and GHG emissions footprint to those of conventional designs[xvii,xviii]. Table 2.3 compares the GHG emissions of each technology. Although upgrading the technology of future power plants can assist us in decreasing emissions, because the CO_2 emissions that even an efficient plant produces are far too high to be a sustainable power source in an environmentally sustainable scenario[xix].

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[2] Variants of conventional pulverized coal combustion technologies, based mainly on subcritical steam conditions (Mills and House, 2014).

[3] Turkey's coal-fired power plants emit 132 Mt CO_2 to produce 76.26 TWh electricity. The German counterparts emit 317.4 Mt CO_2 to generate 284.91 TWh. However, Turkey's most recent coal power plants that are established after 2014 are using supercritical technology (Ersoy, 2015).

Table 2.3: The performance of various combustion technologies

	Sub-critical	**Supercritical**	**USC**	**A-USC**	**IGCC**
Thermal efficiency, % (HHV)	36.2	38.5	39.2	42.7	46
Volume at boiler outlet, actual m^3/min	66,700	61,400	60,400	55,100	-
NO_x and SO_2, kg/MWh	0.127	0.121	0.118	0.109	0.120
CO_2, kg/MWh	900	851	836	763	750

An environmentally sustainable scenario, for example, as outlined in *Energy Technology Perspectives 2017*,[xx] requires that the world-wide power sector have CO_2 emissions approaching zero. Near zero emission sources include renewable and nuclear power and fossil fuel sources with CO_2 capture. Carbon capture, utilization and storage (CCUS) technologies that remove CO_2 from the power source and either use the CO_2 for an industrial purpose, or, for the great majority of CO_2 captured on a global scale, inject it into deep saline aquifers for long-term storage. This technology cannot help in highly distributed sectors such as transportation; however, it shows a promising progress in the power and industrial sectors[xxi]. One notable advantage of CCUS is that it can be applied to many existing power plants and decrease their carbon footprint to a great extent. According to Koelbl et al.[xxii], all integrated assessment models (IAMs) have consistently predicted that the cumulative capture by CCUS technologies will exceed 600 Gt CO_2 by 2100.

Carbon capture (CC) technologies can be implemented on gas-fired or coal-fired power generation plants; however, due to higher CO_2 concentration in the flue[xxiii], it is much more expensive to separate CO_2 from a natural gas turbine than a coal-fired power plant.[xxiv] Each CC technology can be associated to one of following approaches:

- **Pre-combustion:** Generate a synthesis gas from fuel prior to combustion, and then separate and remove CO_2 from the synthesized gas.
- **Oxy-fuel:** Using pure oxygen instead of air, which has nitrogen, can produce high CO_2 concentration in the flue gas at the exhaust.
- **Post-combustion:** Captures CO_2 from the gas after combustion and before release. Post-combustion methods are retrofittable to the existing power plants.

Between all carbon capture technologies, the focus of this study is on aqueous Monoethanolamine (MEA) scrubbing of flue gas, which is commercially available[xxv]. Pre-combustion and oxy-fuel technologies are not considered, as these technologies require being considered at the design time. For instance, coal gasification integrated combined-cycle (IGCC) cannot be retrofitted onto an existing plant as it replaces the steam coal plant; therefore, economically speaking, it is not possible.

In this study, we consider all established coal-fired power plants, as of 2018, that consume coal of any type[4]. Multiple choices are given to these power plants in the context of Turkish energy market. Power plants can choose any of the following solutions:

1. Not installing any CC facility and buying credits form the emissions trading market.
2. Installing CC facilities and participating in the CO_2 trading market as sellers.
3. Installing CC facilities and transferring captured CO_2 to the nearest storage locations (e.g., lignite reserves).
4. Installing CC facilities and selling the captured CO_2 to oil companies to enhance their oil extraction (CO_2-enhanced oil recovery (EOR))

The captured CO_2 can be handled in a supercritical state to be sequestrated. Sequestration is done in three ways: geological sequestration, ocean sequestration, and mineralization. In this manuscript, we only consider geological sequestration.

We develop a mixed-integer nonlinear programming model that helps in the decision-making process to select a proper CC configuration and decide whether to exercise carbon utilization (CCU) or carbon storage (CCS) strategies.

3. Model Description

In this manuscript, 33 coal-fired power plants in Turkey are considered with a total installed capacity of 27.363 GW. According to our estimation, these power plants should release *ca.* 134 Mt of CO_2 each year into the atmosphere. Our plant-level calculation deviates from IEA reports by 2 Mt (*ca.* 1.5%) as new power plants' emissions are estimated based on the utilized technology and consumed coal grade. The plant-level emission data has been collected from the CARMA database.

The combustion technology of coal-fired power plants in Turkey falls into one of these major groups: Pulverized coal with subcritical, Pulverized coal with supercritical steam and the circulating fluidized bed (CFB). There are few exceptions such as Cenal power plant that uses Ultra-supercritical steam and Can-2, which is a combined cycle power plant. Therefore, we assign each power station to one of the following three groups:

- **PC:** all conventional coal-fired power plants (with DeSOx/DeNOx[xxvi]),
- **AD:** advanced power stations such as (ultra)supercritical, PFBC, CFB, etc.,
- **CCPC:** cogeneration power plants.

We ignore integrated gasification combined cycle (IGCC) technology in our study since there is no power plant that exploits this technology as of 2018.

Although the cost of capturing CO_2 is often more than the cost of transportation and storage combined, yet the distance between major CO_2 producers and the storage/utilization areas can influ-

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[4] The total CO_2 emission of Turkey in 2014 is 307.1 (Mt CO_2). Form this total value, 132.1 (Mt CO_2) is emitted in electricity and heat sector. This value is almost equal to 132 (Mt CO_2) that comes from combusting coal. (Source: IEA CO_2 emission from fuel combustion, 2016 ed.)

ence the cost to some extent. Thus, finding the optimal transportation plan can assist us with keeping transportation-related expenditures under control. Among major CO_2 emitters, we solely consider coal-fired power plants and ignore cement or iron-steel industries. For storage locations, we adopt suggested candidates by Kök and Vural (2012)[xxvii]. We also assume only one domestic EOR candidate, the Batı Raman oil field in Batman. In fact, CO_2 injection has been used first in Turkey after the USA in the 80's. Currently, the injected CO_2 is transferred from the Dondan field, 90 km away from the Batı-Raman limestone field. In this study, unlimited CO_2 injection capacities for storage locations are presumed.

The suggested Storage and Utilization locations are as follows:

- Storage Candidates:
    - Manisa Soma Lignite reserve
    - Kütahya Tavşanlı lignite reserve
    - Bursa lignite reserve
    - Çayırhan lignite reserve
    - Kırşehir lignite reserve
    - Muğla-Yatağan lignite reserve
    - Zonguldak hard coal reserve
    - Natural gas and oil fields in Thrace region (Kırklareli)
    - Kahramanmaraş-Elbistan lignite reserve
- Utilization Candidate:
    - Batı Raman oil field (EOR)

According to Zero Emission Platform[xxviii], the unit cost of installing onshore pipeline is $5.4d/180$ (US$/ton) where d is the distance in km. CO_2 transportation through offshore routes is excluded because of economic reasons. The distance between power plants with storage and utilization centers are extracted from the Google Map using vehicle routes as a proxy for the pipeable routes. Also, a storage cost of US$10 per metric ton is adopted from Voll et al.[xxix].

Since considered coal-fired power stations are producing electricity, pre-combustion and oxy-fuel technologies are inappropriate, as these technologies need modifying current configurations. The only viable choice is to use post-combustion technology, which is retrofittable to available power plants. Among all post-combustion technologies, we consider aqueous Monoethanolamine (MEA) scrubbing as it is commercially ready. The proposed model decides the installed capacity of the CC facility since the desired amount of flue gas can be redirected. Moreover, the carbon capture rate of the MEA systems in the literature is reported less than 96%[xxx].

The cost information for the mentioned CC technology has been extracted from Jeremy and Herzog (2000)[xxxi]. As the focus of this study is on CC technology, we consider only CC-related costs[5]. Assuming MEA scrubbing can be annexed to an available coal-fired power plant, we remove the

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[5] For instance, we ignore costs of turbine or boiler as they are already in place in current power plants.

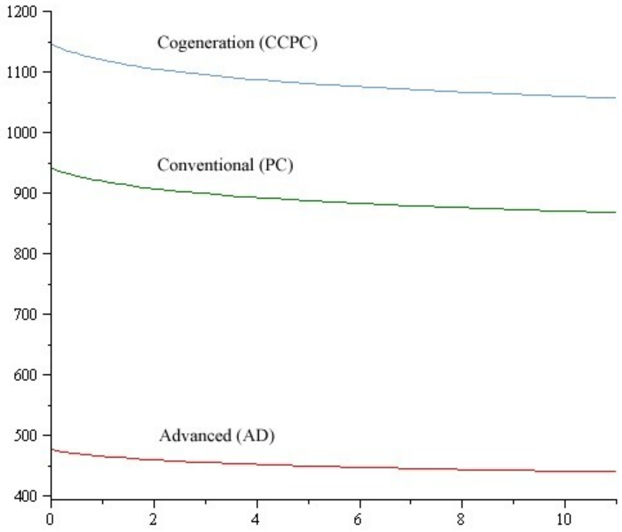
cost of shared components; therefore, we recalculate CC cost for each technology as the cost difference between facilities with and without CC in our model in Table 3.1.

Table 3.1: Cost specification of coal-fired power plants

Coal-fired power plants	**Tech. (τ)**	**Investment Cost (US$/kW)**	**Fixed O&M (US$/kW/yr)**	**Variable O&M (US$/kWh)**
Coal conv. with DeSOx/DeNOx	PC	1150	48.0	1.22
Coal conv. with DeSOx/DeNOx + CCS	PC+CCS	2090	80.0	1.53
CCS only	**PC**	**940**	**32.0**	**0.0011**
Coal cogeneration	CCPC	1155	49.0	1.5
Coal cogeneration + CCS	CCPC+CCS	2300	82.0	1.88
CCS only	**CCPC**	**1145**	**33.0**	**0.0014**
Coal advanced (Supercritical, PFBC)	AD	1584	47.5	0.75
Coal advanced + CCS	AD+CCS	2060	90.0	1.13
CCS only	**AD**	**476**	**42.5**	**0.0014**

The total investment cost (INC) in all power plants is modeled with respect to their combustion technology. This investment cost is discounted according to the installation time. To consider the learning effect on the unit investment cost, the learning curve with respect to cumulative installed capacity is taken into account. In the proposed model, similar to Neij (2008)[xxxii], we assume a learning rate (LR) of 5% for the investment cost of all coal-fired power plant technologies (i.e., PC, CFB, and CCPC). Due to the nonlinearity of the learning curve, the resulted model is nonlinear. Figure 3.1 demonstrates the evolution of the unit investment cost for each of combustion technologies with respect to cumulative installed capacity and *LR* = 5%.

Figure 3.1: The plot shows the effect of cumulative installation on the unit investment cost.



In addition to the regular fixed operation and maintenance cost (FOM), each power plant has to incur CC-related FOM cost annually for the maximum installed capacity of the CC unit. In our model, the FOM cost of each power plant is discounted based on the establishment year and the given discount rate. Also, the variable operation and maintenance costs (VOM) is formulated such that model has the flexibility to utilize CC units, fully or partially in each time period.

The total storage cost (STO) is formulated based on the pairs of sources (each power plant) and destinations (all storage points). The unit storage cost is set to US$10,000/kton and the model determines the amount of CO_2 that should be stored in each storage location at a given time.

By selling captured CO_2 to oil fields for EOR purposes, CO_2 can become an income source for stockholders. We assume a selling price of US$5,000/kton. In this study, we have only one utilization candidate, but we can increase the number of candidates upon request (e.g., exporting the captured CO_2 to Iraq to be used by oil industries in Mosul). The model determines the amount of sold CO_2 to each utilization facility and discounts the profit (SEL) based on the utilization time and discount rate.

Although CO_2 trading market is not implemented in Turkey yet, a possible CO_2 market is taken into consideration. In fact, the Directorate General of Environmental Management under the Ministry of Environment and Urbanization is currently investigating an emissions trading system to be put into practice in the near future (MEU, 2012[xxxiii]). We allow power plants to buy, or sell in case of excessive absorption, carbon credits from this market to keep their emissions under the functional cap. We assume that market price of carbon increases through time from an initial value of US$25,000/kton with the rate of 3%. The cost of procured credits from the market (BUY) is discounted for each power plant with regard to the transaction time and the given discount rate.

The last component of the objective function represents the transportation and logistics costs (TRA). The installed pipelines should be able to support the maximum flow for each pair of source and destination whether for storage or utilization purposes.

By combining all previous terms, the objective function is formulated as a minimization function, which corresponds to the negative of net present value (NPV).

$$\text{Min } Z = INC + FOM + VOM + STO - SEL + BUY + TRA \quad (1)$$

The proposed model has to consider a set of constraints regarding emissions, market regulations and technical limitations. We confine the CC capacity by the maximum power generation capacity of each power plant. We put an upper bound on the buying option from the emissions trading market. In our model, we make sure that the carbon capturing facility in each power plant is installed prior to the utilization or storage time. Our model also ensures that captured and bought/sold carbon in each power plant at a given time is equal to the admissible carbon emission cap.

Similar to Ağralı et al., (2017)[xxxiv], we assume a cap-and-trade system, in which the imposed CO_2 cap at beginning of planning horizon is equal to the total emissions of each power plant and decreases from that initial value every following year by the rate of 3%.

4. Solution without Learning

The results of the model without endogenous learning (LR = 0%) show that by spending US$7,118.92 million in 20 years, we can prevent exceeding the specified CO_2 cap. The optimal objective value (Z*) is broken down in Table 4.1. The values in parentheses are income.

Table 4.1: Cost components of the optimal solution (values in parantheses are income).

The optimal objective value (million US$)	7,118.92
Investment cost	11,227.02
Fixed O&M cost	8,608.08
Variable O&M cost	1,941.68
Storage cost	8,827.40
Transportation cost to storage locations	1,958.43
Transportation cost for utilization	5,757.43
Selling CO_2 for EOR purposes	**(1,899.47)**
Selling CO_2 credits to the market	**(29,301.67)**

At optimal solution, power plants who decided to install CC units, choose capacities that cover their whole electricity generation capacities. Table 4.2 demonstrates the optimal solution when learning is ignored. Since VOM cost is negligible in comparison with the unit installation cost, power stations better off utilizing their full CC units' potential in the years following the installation time.

As we can see, nine power stations skip CC unit installation and buy the required amount of CO_2 from the market when it is required. The source and destination pairs are arranged such that transportation-related costs are at minimum.

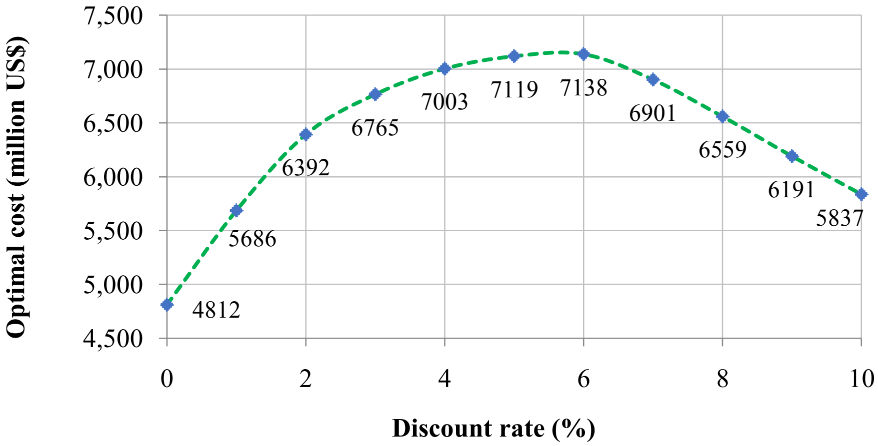
5. Sensitivity Analysis of Discount Rate

The discount rate (*r*) analysis, in Figure 5.1, illustrates a significant impact on the system cost. Increasing *r* from zero to 6% causes the system cost to grow as well; however, increasing *r* beyond 6% decreases the system cost. As the discount rate increases, the investment on CC units decreases and companies would prefer to buy CO_2 credits from the market in later periods when the money has a lower value. The most negative effect on the overall system cost has happened when the discount rate is about 6%.

Table 4.2: The optimal solution without learning. N/I means CC unit is not installed

Power Plant	CP_i^M	Install at t	Storage locations	Utiliza-tion
Çatalağzı, Zonguldak	N/I			
Afşin-Elbistan A K Maraş	1.335	1		Yes
Afşin-Elbistan B K Maraş	1.44	1		Yes
Çan Çanakkale (18 Mart)	0.32	1	Manisa, Soma	
Orhaneli Bursa	0.21	3	Bursa lignite res.	
Seyitömer, Kütahya	0.6	3	Kütahya Tavsanlı	
Tunçbilek Kütahya	0.365	4	Kütahya Tavsanlı	
Kangal	0.537	1		Yes
Soma A&B Manisa	N/I			
Kemerköy Muğla	0.63	1	Muğla	
Yeniköy Muğla	0.42	2	Muğla	
Yatağan Muğla	0.63	2	Muğla	
Sugözü-İskenderun	N/I			
Çolakoğlu-2, Kocaeli, Gebze	N/I			
Silopi	N/I			
Biga-Değirmencik	0.405	1	Bursa lignite res.	
ZET1& ZET2, Çatalağzı, Zonguldak	1.39	1	Zonguldak	
Bekirli - Biga - Çanakkale	1.605	1	Manisa, Soma	
Atlas İskenderun, Hatay	1.2	1		Yes
Çayırhan, Ankara	0.62	1	Çayırhan & Kırsehir	
İzdemir-Aliağa, İzmir	0.35	1	Manisa, Soma	
Polat-1 PP, Tunçbilek, Tavşanlı, Kütahya	N/I			
Tufanbeyli, Adana	0.45	1		Yes
Afşin-Elbistan C,D and E, K Maraş	N/I			
Amasra, Bartin	1.3	1	Zonguldak	
ZET3, Çatalağzı town, Zonguldak	1.4	1	Zonguldak	
AYAS-1 power plant, İSKEN	0.626	1		Yes
Anadolu Group, Gerze Power Plant	N/I			
Göynük Power Plant, Bolu - New	0.27	1	Çayırhan	
Hidro-Gen Soma, Soma, Manisa	0.5	1	Manisa, Soma	
Cenal Power Plant, Çanakkale, Biga	1.32	1	Bursa lignite res.	
Yunus Emre Thermal PP, Eskişehir	0.29	1	Çayırhan	
Can-2 Power Plant, Çanakale	N/I			

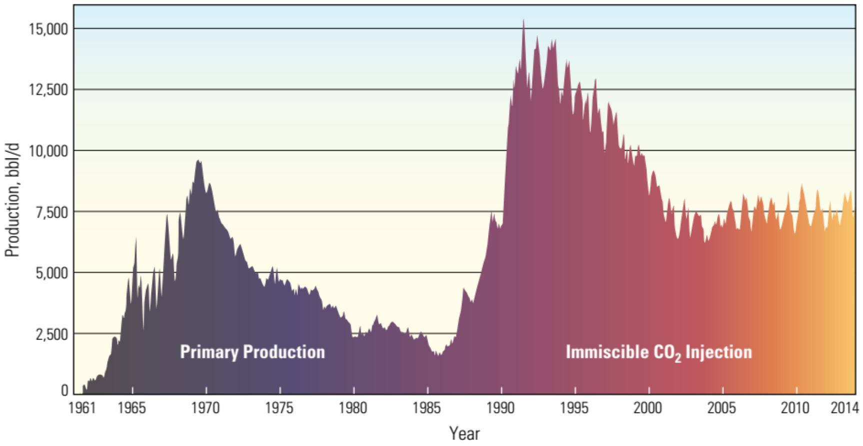
Figure 5.1: Sensitivity of optimal system cost to changes in discount rate.



6. Sensitivity Analysis of Utilization Capacity

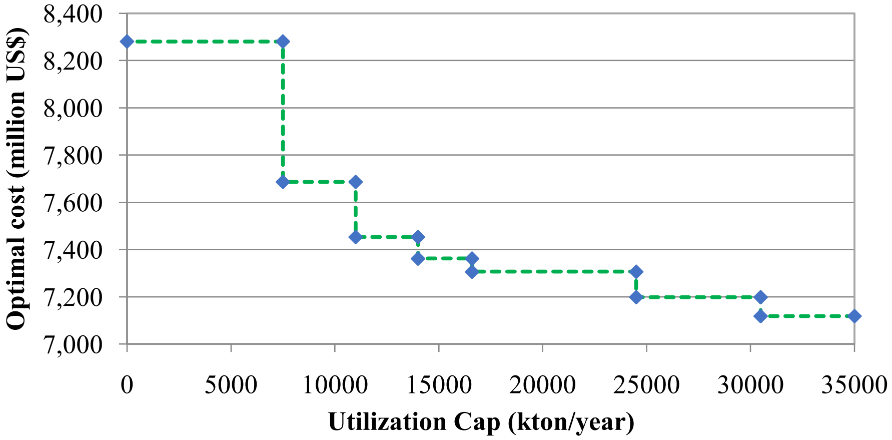
In this study, we consider an unlimited capacity for the storage and utilization. Despite the fact that the data availability of Turkish oil fields is not as complete as the USA, there is some historical information, which can help us with providing insightful analysis for the government. The Batı Raman field is using EOR treatment since 80's. Figure 6.1 separates the heavy oil production in the Batı Raman before and after the CO_2 injection activities commenced. According to Perera et al., (2016)[xxxv], the cumulative injected CO_2 is 124 mmscf per day which is 2,348,183.22 metric ton of CO_2 per year.

Figure 6.1: Oil production from the Batı Raman field through years.
Source: Ansarizadeh et al., (2015)[xxxvi]



Since the Batı Raman field data is incomplete, we provide the optimal system cost (Z*) regarding various utilization capacity values in Figure 6.2. When the utilization capacity is zero, the captured carbon should be either traded in the emissions trading market or stored; hence, the system cost is at maximum. Also, an annual utilization capacity over 30,484 kton is beyond the capture capacity of all coal-fired power plants.

Figure 6.2: The sensitivity analysis of utilization cap.



Assuming the Batı Raman reported capacity, CO_2 utilization is not seeming a viable alternative as the transportation cost overshadows the income. To prepare the Batı Raman oil field, we have to expand the injection capacity. For the sake of tractability, we assume no utilization cap in the rest of the manuscript.

7. Solution with Learning

In the developed model, power plants can separately optimize their decision variables with a given knowledge of the future investment costs. This provides a new opportunity for the modeler to analyze the strategic behavior of power plants under different scenarios like studies based on agent-based simulation techniques[xxxvii,xxxviii,xxxix]. In this setting, players may act myopic and optimize their profits rather than the whole system or an independent central system coordinates their actions such that it optimizes the total system cost.

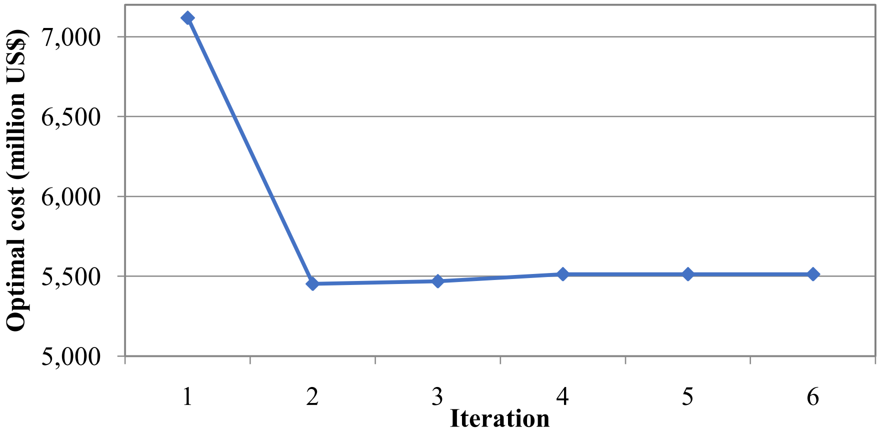
a. Myopic Solution

In this section, we assume each power plant is considering its cost and not the whole system. Thus, power plant *i* has belief-*i* ($\pi_i \in \Omega$) by which it predicts the time and size of the CC units of other power plants. According to given π_i, power plant-*i* solves the model and determines the optimal decision (i.e., when and how much to invest in CC technology). As one can see, this is a Stackelberg game, in which the collective beliefs of all power plants change the state of the system, in this case, the unit investment cost, and the set of beliefs consecutively.

One can find the equilibrium solutions of this game iteratively. With an initial assumption for each power plant about other players (i.e., assuming no power plant is going to construct CC facility), we solve the model. Next, we have a new cumulative installed capacity for CC facility at time t. Then, we update the investment cost for each power plant with the combustion technology τ at time t. Finally, with new investment cost coefficient, we solve the proposed model again. We repeat this cycle until the optimal solution does not change between two consecutive iterations. This termination condition means a stable state has been reached and no power plant changes its plan for the CC size and its installation time given the decisions of others stays the same; hence, the unit investment cost of CC units and π_i will not evolve.

Figure 7.1.1, describes a myopic solution when the initial belief for all power plants at iteration #1 is that no power plant is planning to install a CC unit and the learning rates are adopted from Neij (2008)[xl]. The termination condition is achieved once the proposed cycle is repeated for six iterations. According to results, we had a steep drop in the optimal cost between iteration one (US$7,119 million) and two (US$5,453 million), then it inclined slightly in the next iterations. Considering endogenous learning with non-cooperative players, the system cost at equilibrium state would be US$5,514 million.

Figure 7.1.1: Evolution of the optimal cost of myopic approach through iterations.



As depicted in Figure 7.1.2, a lower unit installation cost causes the total CC capacity of conventional power plants to increase from 7.077 GW to 8.11 GW between the first and second iterations. We should also note that all power plants tend to construct CC units together to maximize the effect of "learning by doing" on the unit investment cost. Therefore, early adopters with small capacities (followers) would prefer to defer their construction time to later years to be synchronized with big players (leaders).

b. A Centralized Decision Making

A central decision making system can help power plants to reach a lower overall system cost. To solve such a centralized model, we allow the optimization solver to find the optimal set of beliefs ($\pi_i \in \Omega$). The resulted model is MINLP.

With respect to provided data, the global optimal cost is US$5,302 million. The optimal set of belief is to open all CC facilities at the same time in the first year, if it is economical. As one can perceive from Figure 7.2.1, the optimal cost (Z*) monotonically decreases through iterations and satisfies the termination condition earlier than myopic approach.

Figure 7.1.2: The cumulative installed capacity of all CC units on coal-fired power plants with PC technology through time. Different colors depict different iterations. The vertical and horizontal axes are the cumulative installed capacity, and the planning horizon, respectively.

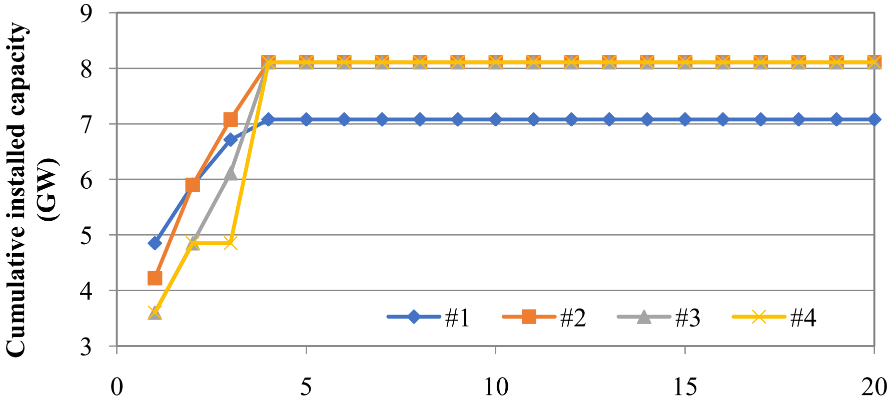
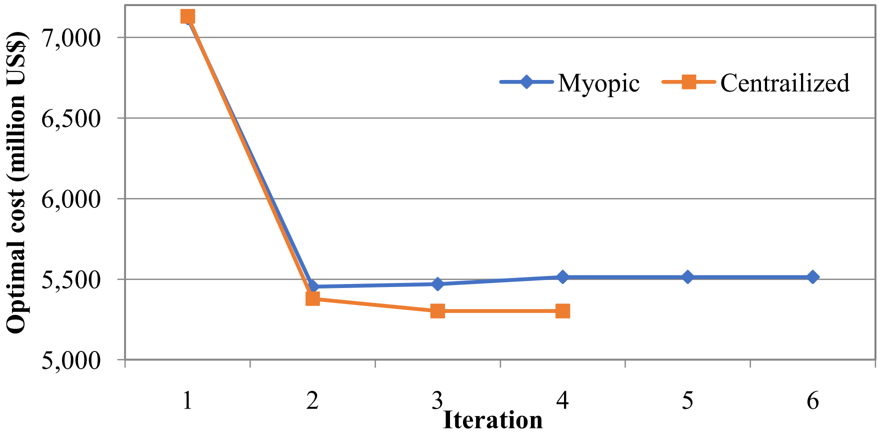


Figure 7.2.1: Comparing the evolution of optimal costs between myopic and centralized approaches through iterations.



8. Summary

According to obtained results, we can provide the following managerial insights:

- Having an emissions trading market is critical for a successful implementation of the carbon capturing technology in Turkey.
- The discount rate has an opposite correlation with CC unit installation. The higher the discount rate, the less likely power plants invest in CC units as the value of investment in early periods worth more.

- Due to distance and transportation-related costs, the Batı Raman field has to expand CO_2 injection capacities in order to become an appealing alternative for carbon utilization. Approximately, we need to inject CO_2 three times of the current rate to become an economically viable option. Also, considering the relatively short distance between the Batı Raman field and Mosul in Iraq and the level of oil extraction in Iraq, Turkey should consider exporting CO_2.
- When power stations act independently, small players synchronize their investments with big players to benefit from the learning factor and cheaper investment costs.
- Coordinated actions of all players would favor CC unit installation and decrease the overall system cost.

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