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Techno-economic feasibility study of the commercial-scale oxy-cfb carbon capture system in Turkey

Türkiye'de ticari ölçekli oksi-day karbon yakalama tesisinin tekno-ekonomik fizibilite çalışması

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Techno-Economic Feasibility Study of the Commercial-Scale Oxy-CFB Carbon Capture System in Turkey (EN)

Highlights

- *Oxy-CFB plant has a lower plant cost, O&M cost, COE and LCOE, for CO_2 capture compared to amine based carbon capture plant*
- *The efficiency penalty for oxy-CFB is 10% and for amine-based capture, it is 12%.*

Graphical Abstract

The basic economic performance indicators for three different types of CFB plant generating 550 MWe net power with a carbon capture rate of 90% were investigated.

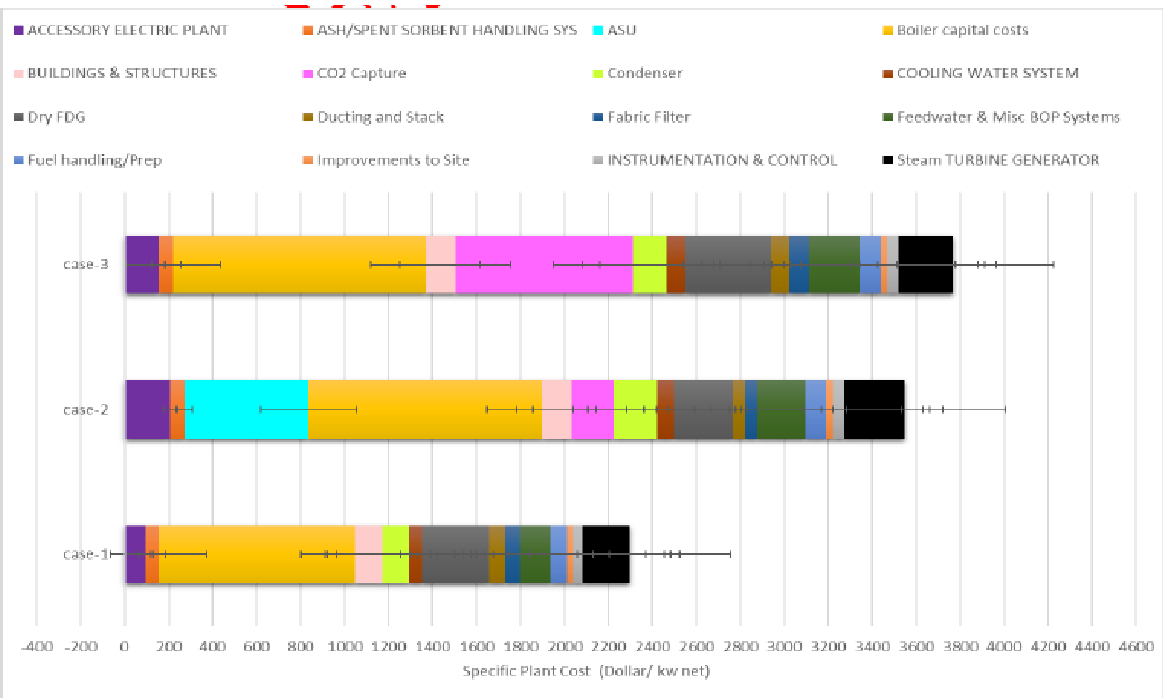

Figure. Specific plant cost of proposed three cases.

Aim

The aim of the study was to perform the techno-economic feasibility analysis of the oxy-CFB power plant.

Design &Methodology

The economic model are based on cost scaling and Discounted Cash Flow analysis.

Originality

This is the first study that has used Turkish lignite in an oxy-CFB carbon capture plant economic analysis

Findings

The oxy-fuel combustion system is economically more advantageous than amine-based capture system

Conclusion

The obtained results indicated that 54% and 52% increase in terms of total plant cost and COE respectively in the oxy-CFB plant when compared to air fired-CFB without carbon capture. The efficiency penalty for oxy-CFB is 10%. Oxy-CFB plant has a net efficiency 2% point higher than amine-based CO2 capture systems

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Türkiye'de Ticari Ölçekli OKSİ-DAY Karbon Yakalama Tesisinin Tekno-Ekonomik Fizibilite Çalışması

Araştırma Makalesi / Research Article

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ÖZ

Oksi-yakıt yanma teknolojisi kömür yakıtlı enerji santrallerinde karbondioksit emisyonlarının azaltılması için fosil yakıtların temiz kullanımını sağlayayabilecek umut vaat eden bir teknolojidir. Sirkülasyonlu akışkan yataklı (DAY) kazanlar, oksi-yakıt yanma tasarımını başarıyla kullanabilen güç üretim teknolojilerinden biridir. Bu çalışmada, 550 MWnet güç üreten ve % 90 CO_2 yakalama oranına sahip ticari ölçekli bir oksi-yakıt yanma dolaşımlı akışkan yataklı (oksi-DAY) santralin tekno-ekonomik fizibilite analizi yapılmıştır. Oksi-pulverize sistem enerji santrallerinin ekonomik analizi birçok raporda incelenmiştir. Fakat, oksi-DAY sistem enerji santralleri maliyeti hakkında çok fazla çalışma bulunmamaktadır. Bu çalışma, yeni kurulumu planlanan bir oksi-DAY karbon yakalama tesisi ekonomik analizi için ilk kez bir Türk linyiti (Orhaneli kömürü) kullanmıştır. Ekonomik performans göstergeleri, maliyet ölçeklendirme ve İndirgenmiş Nakit Akışı analizi yöntemleri ile bulunmuştur. Temel olarak üç durum analiz edilmiştir. İlk durumda, bir baz senaryo (CO_2 yakalama ünitesi olmayan hava ateşlemeli DAY tesisi) tasarlanmış, bu temel senaryoya dayanarak diğer durumlar modellenmiştir. Böylece, klasik hava ateşlemeli DAY sisteminden CO_2 yakalama ve sıkıştırma üniteli oksi-DAY sistemine geçişin ekonomik uygulanabilirliği değerlendirilmiştir. Yanma sonrası monoetanolamin (MEA) bazlı CO_2 yakalama sistemi, oksi-DAY CO_2 yakalama sistemi performansını karşılaştırmak için bir kıyaslama çalışması olarak incelenmiştir. Elektrik maliyeti (COE), indirgenmiş elektrik maliyeti (LCOE) ve CO_2 yakalama maliyeti gibi ana uygulanabilirlik parametreleri hesaplanmıştır. Elde edilen sonuçlar, klasik hava ateşlemeli DAY tesisi ile karşılaştırıldığında, oksi-DAY tesisi toplam tesis maliyeti ve COE açısından sırasıyla % 54 ve % 52'lik bir artış göstermektedir. Amerikan Enerji Bakanlığı (DOE)'nın SC-PC sistemler için belirlediği COE hedef değeri göz önüne alındığında, tasarlanan oksi-DAY enerji santrali COE değeri hava ile çalışan hedef SC-PC COE değerinden % 45 fazladır. Tasarlanan Oksi-DAY tesisi için verimlilik cezası % 10'dur. Oksi-DAY tesisi, amin bazlı CO_2 yakalama sisteminden % 2 puan daha yüksek net verimliliğe sahiptir. Amin bazlı sistemde; sermaye maliyeti, LCOE ve CO_2 yakalama maliyeti oksi-CFB tesisinden daha yüksektir. Sonuçlar, oksi-DAY enerji santralinin, amin bazlı yakalama tesisine kıyasla karbon tutma maliyetlerinin daha düşük olduğunu göstermektedir.

Anahtar Kelimeler: Oksi-yakıt yanma, dolaşımlı akışkan yatak, karbondioksit tutulumu, seviyelendirilmiş elektrik maliyeti, tekno-ekonomik analiz.

Techno-Economic Feasibility Study of the Commercial-Scale Oxy-CFB Carbon Capture System in Turkey

ABSTRACT

Oxy-fuel combustion is a promising technology for the reduction of carbon dioxide emissions, in coal-fired power plants that allow the clean use of fossil fuels. Circulating fluidized bed (CFB) boilers are one of the power generation technologies that can use oxy-fuel combustion design successfully. The purpose of this paper is to perform the techno-economic feasibility analysis of the commercial-scale oxy-fuel combustion circulating fluidized bed (oxy-CFB) power plant generating 550 MWe net power with a carbon capture rate of 90%. So far, economic analysis of oxy-PC power plants has been studied by researchers at many reports. Nevertheless, the cost of an oxy-CFB power plant has rarely been studied.This is the first study that has used Turkish lignite (Orhaneli Coal) in an oxy-CFB carbon capture plant economic analysis. The basic economic performance indicators were investigated. The Models are based on cost scaling and Discounted Cash Flow analysis. Three cases were analyzed: In the first case, A base scenario (air-fired CFB plant without CO_2 capture) is considered and then based on this baseline scenario the other scenarios are taken into account. The economic viability of transition from the classical air-fired CFB plant system to oxy-CFB with CO_2 capture and compression plant is evaluated. The post-combustion monoethanolamine (MEA) based CO2 capture system is investigated as a benchmark study to compare oxy-CFB capture system performances. The main applicability parameters such

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as cost of electricity (COE), levelized cost of electricity (LCOE) and the cost of CO_2 capture for each case are calculated. The obtained results indicated that 54% and 52% increase in terms of total plant cost and COE respectively in the oxy-CFB plant when compared to air fired-CFB without carbon capture. Considering the COE, the designed oxy-CFB power plant is greater than the air-fired SC-PC (without capture) plant by more than 45% (DOE target). The efficiency penalty for oxy-CFB is 10%. Oxy-CFB plant has a net efficiency 2% point higher than amine-based CO_2 capture systems. In amine-based CO_2 capture system; The capital costs, LCOE, and cost of CO_2 captured are higher than the oxy-CFB plant. The results show that the oxy-CFB power plant has a lower cost for carbon capture compared to amine-based capture plant.

Keywords: Oxy-fuel combustion, circulating fluidized bed, carbondioxide capture, levelized cost of electricity, techno-economic analysis.

1. INTRODUCTION

The energy industry uses fossil fuels such as coal, lignite, oil and natural gas as raw material. 40% of the power generation in the World is produced by coal and the coal-fired power plants of which capacity is 2024 GW. Nevertheless, The power plant with 236GW capacity is under construction and with 337GW capacity is in the planning phase (2018). China, US and India have the largest coal-fired capacity in the world respectively. In 2018, the coal-fired power plant with a total capacity of 31GW was retired. Many countries, especially China, have been shutting down old technology and less efficient power plants. Instead, high-efficiency (USC, SC) power plants with new technology are being built [1]. As stated in the energy forecasts, In the near future, most of the energy need will be provided by coal.

Turkey has the sixth-largest electricity market in Europe, with 85.2 GW of installed power [2]. Most of the electricity production in Turkey is provided using coal. The majority of Turkey's coal reserves consist of lignite coal, which was 95% of the total coal produced [3].

In 2017, Turkey was the third major lignite producer and the second major lignite consumer following Germany [4]. Turkey continues to work on the installation of many new coal plants 67 GW proposed and 3 GW under construction (2016) [5]. Therefore, Turkey needs clean coal-fired power plant systems in order to use this potential. According to IEA Turkey report (2016), in recent years, Turkey attaches importance to the implementation of clean coal technologies. For this purpose, new lignite and asphaltite-fired power plants with supercritical technology are installed. CFB technology is used in new power plants established by the private sector. In Turkey, there have been some studies on clean coal technologies especially on (CFB) combustion technology of coal/biomass R & D activities in the coal clean by (Turkey Scientific and Technical Research Council of Turkey) TUBITAK [6].

About 34% of global greenhouse gas emission is caused by the combustion of coal. CO_2 generated by the combustion of coal is the main constituent of greenhouse gases [7].

Carbon Capture and Storage (CCS) is a significant technology for decreasing the greenhouse gas effect in the atmosphere. It ensures the usage of fossil fuels without the pollutant effect.

CCS techniques that avoid large quantities of CO_2 from being emitted to the atmosphere include three basic technologies. These are a separation of CO_2 before the combustion (pre-combustion), combustion using oxygen instead of air (Oxy-fuel combustion) and CO_2 capture from flue gas (post-combustion) [7].

Oxy-fuel combustion technology is one of the main methods for CCS that ensures almost zero-emission. The main principle of oxy-fuel combustion technology is to **use** oxygen instead of air for combustion. Control of the boiler temperature is achieved by recycling a portion of the flue gases (about 60-70%) to the boiler. The flue gas is basically comprised of water vapour and CO_2 and this reduces the energy consumption in CO_2 separation. CO_2 density is directly related to air ingress and oxygen purity. The flue gas contains typically 65 - 85 vol% CO_2 (dry basis). In the oxy-fuel combustion process, flue gas is generated at 20% of the amount compared to the classic air-fired combustion process. This case makes carbon capture easier and reduces the energy consumption of CO_2 separation [8] [9]. Figure 1 shows the schematic of the oxy- boiler with flue-gas recycling.

The flue gas recovery system and the air separation unit (ASU) are the most significant differences in the oxy-combustion process. Recycling the flue gas to the boiler ensures heat transfer and mass flow. The flue gas recycling model takes place in two ways: cold-recycle and warm-recycle. The corrosive effects of the recycling flue gases may damage to the boiler. To avoid this effect, according to the corrosive effect of coal, the process configuration is changed.

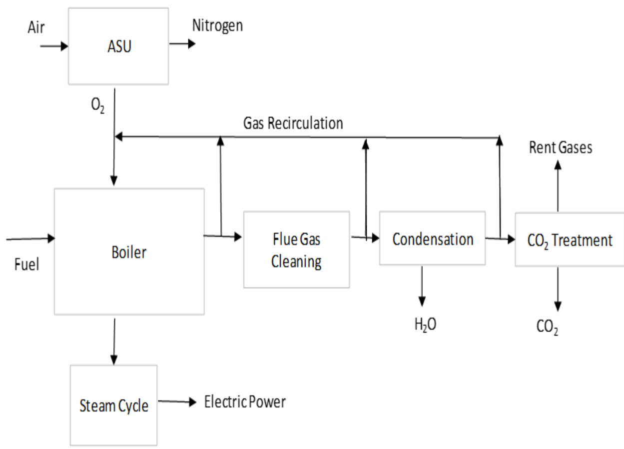

Figure 1. The Schematic of the oxy- boiler with flue-gas recycling [10]

In the case of cold-recycle, recycle process is occurred after the FGD unit. Thus, the flue gas recycled to the boiler includes very little moisture and corrosive effect. In the case of warm-recycle, the flue gas recycled to the boiler is removed without entering the bag filter. The flue gas recycled to the boiler includes moisture. In this model, the recycled flue gas contains high humidity and SO2 concentration. For very low sulfur content coals, warm-recycle flue gas can be used. The corrosive effect is correlated with coal's high sulfur content. Therefore, for high sulfur content coal, the recycling flue gases must be cleaned. Especially coal sulfur content procures modification in the process configuration [11][12].

The distinguishing feature of the oxyfuel combustion process is the removal of nitrogen in the oxidant stream. NOx emissions are caused only by little air leaks in the boiler and mainly coal content fed to the boiler. At the CFB processes, lower bed temperature can be obtained due to the recycling the flue gas. Thermal NOx emission is produced at elevated temperatures. Due to the low combustion temperature of CFB, little thermal NOx is generated. Controlling operation temperature and O2/fuel rate performs lower NO emission. In oxy-CFB, stream-oxygen staging method is effective for managing NOx emission. Therefore, expensive De-NOx systems are not needed for an oxy-CFB plant. [13][14][15].

In the oxy-fuel combustion process, the required oxygen is produced by a cryogenic ASU. Although different techniques such as membrane technology and chemical looping are being investigated, cryogenic ASU is still used to produce large amounts of oxygen. The power consumption of the cryogenic ASU is about 200-225 kW/h [16] [17].

Using of low oxygen concentration (lower than 30%) in oxy-combustion technology is called "first-generation oxyfuel power plants" [18].

The use of higher oxygen concentration (30-50%) in oxy-combustion technology reduces the energy penalty and the amount of recycled flue gas. This is known as "second-generation oxy-combustion power plants". Reducing the energy consumption of auxiliary units was started by "second-generation oxyfuel power plants" design. Notable improvements have been obtained for CO_2 compression and purification unit (CPU) and cryogenic ASU [19]. The O2Gen (Oxy-CFB) project completed in 2016 is a successful example. Owing to the high oxygen concentration, the boiler size decreases. In this project, with high oxygen concentration and process integration method, the energy penalty decreased from 10.5% to 7.3% [20].

When the higher oxygen concentration is used, the flue gas flow is smaller even if the constant thermal load is provided. Therefore, the smaller boiler size can be obtained. Moreover, using the smaller equipment (such as a fan) procures to lesser the auxiliary system load. This improves the net efficiency of the power plant [21].

Some issues such as combustion efficiency, pollutant gas formation and desulfurization mechanisms are not clear in second-generation oxy-fuel CFB and further research is needed [18].

Circulating fluidized bed (CFB) boilers have some advantages in the use of oxy-fuel combustion technology. The particle size of the fuel could be much larger compared to a pulverized coal-fired system. Also, the CFB power plants have the flexibility of the fuel type (biomass, biomass-coal blends and various solid wastes etc). Injecting limestone to the bed provides for sulphur retention and because of low temperature in the combustion chamber, NOx emissions are kept under control control [21].

The flame temperature is the major difference between the oxy-PC and oxy-CFB. The flame temperature rises with an increase in oxygen concentration. But for an oxy-CFB, the combustion temperature is under control due to the boiler bed material [10].

The first coal-fired SC-CFB facility was installed in Lagitza (Poland-2009) and SC-CFB plants are under construction in many countries (China, Russia and South Korea). CFB power plants will be a significant agent in the future energy market [22].

Many studies have been carried out on oxy-fuel combustion processes, both on the laboratory scale and on the pilot scale. Figure 2 shows the oxy-CFB pilot-scale plants [21]. Currently, there is no industrial-size Oxy-CFBC facility in the world [9].

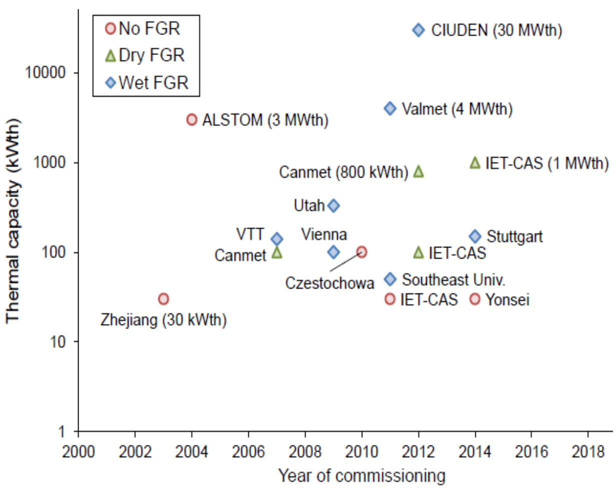

Figure 2. The oxy-CFB pilot-scale plants [21].

CIUDEN (30 MWth-Spain) and Callide (30 MWe-Australia) are the largest scale oxy-combustion circulating fluidized bed (oxy-CFB) facilities tested to date [23][24]. Oxy-fuel combustion technology requires more application and scaling to become a part of the energy production sector.

Air Liquide Engineering (ALE) has evaluated a CO_2 compression and purification unit (CPU) capacity of 200 MWe for the proposed FutureGen 2.0 Project in the USA and they publicly announced that there is no technical obstacle to the commercialization of large-scale CPU in oxyfuel power plants [24].

In some studies in literature, it is stated that the ideal plant capacity for CO_2 capture plant is between 100-500 MWe in terms of viability [25][26]. However, in techno-economic feasibility reports prepared by DOE-NETL, plant capacity is determined as 550 MWe [13]. In this study, based on the DOE-NETL studies, the plant capacity was selected 550 MWnet for power generation.

So far, techno-economic analysis of oxy-PC power plants has been studied by researchers at many reports [8][27][28][29]. Nevertheless, the cost of an oxy-CFB power plant has rarely been studied [17][30].
The novelty of this paper, as a feasibility analysis, is the first use of Turkish domestic coal as a fuel for oxy-CFB power plant.
The objectives of this study are presented as follows:
- For the first time, conducting a techno-economic feasibility study of commercial-scale oxy-CFB facility planning to produce 550 MWe net power using Turkish lignite coal.
- Compare TEA of a CFB power plant to Oxy-CFB and Post-combustion amine-based CFB technologies.
- To contribute to the current techno-economic studies of oxy-CFB

As an alternative to traditional coal-fired power plants, three different types of coal-fired CFB plant are designed. A base scenario (air fired-CFB plant) is considered and the other scenarios are based on this baseline scenario. As a benchmark case, oxy-combustion CO_2 capture system and monoethanolamine (MEA) based CO_2 capture system are assessed. CO_2 capture rate is 90% for both processes.

2. MATERIALS AND METHODS

2.1 Material

The Orhaneli lignite coal was used as raw material. The analyses were performed at TÜBİTAK MAM Energy Institute. The samples were prepared and analyzed according to ASTM D 5865, ASTM D 5373, ASTM D 7582 methods. Table 1 summarizes the thermal, proximate and ultimate analysis of Orhaneli lignite coal [31].

Table 1. Fuel composition and thermal characteristics of Orhaneli lignite

Thermal analysis(MJ/kg)(a.r)	
Higher heating value	18.17
Lower heating value	16.75
Proximate analysis(wt.%)(a.r)	
Moisture	30.40%
Volatiles	32.75%
Fixed Carbon	30.35%
Ash	6.49%
Ultimate analysis (wt%) (d.b)	
Total carbon	69.53%
Hydrogen	4.43%
Nitrogen	1.08%
Sulphur	2.28%
Oxygen	13.35%
Ash	9.33%

a.r: as received d.b: dry basis

2.2. Technoeconomics Analysis Approach

The first part of the study consists of technical simulation. Firstly, process specifications (Plant type, capacity, capture method etc.) are decided and then, performance analysis is carried out. Mass-energy balances, equipment lists, operation conditions are assigned. In the second part, the main applicability parameters such as cost of electricity (COE), levelized cost of electricity (LCOE) and CO_2 capture cost for each case are calculated and compared with each other. The defined economic and financial parameters are used as the main applicability parameters in calculation. The cost estimating methodology is shown in Figure 3.

A base scenario (air fired-CFB plant) is considered and the other scenarios are based on this baseline scenario. Thus, the economic viability of transition from the classical air-fired CFB plant system to oxy-CFB with CO_2 capture and compression is evaluated. The oxy-CFB are also compared to the monoethanolamine (MEA) based CO_2 capture system. The cost of CO_2 capture is calculated for both systems. The plant designs evaluated in this study are as follows;

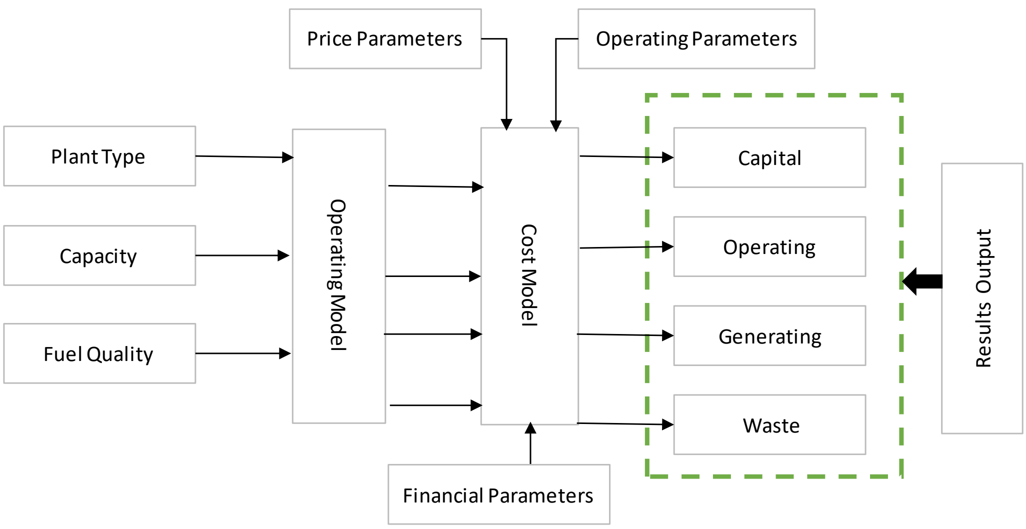

Figure 3. The Cost Estimating Methodology [32].

Table 2. The basic boiler parameters and load factors [37].

Parameters	Units	
Steam cycle efficiency	N/A	0.4695
Excess air	%	12.8%
Oxy excess air	%	8%
Oxycombustion flue gas recycle	%	55%
Infiltration air	%	1.76%
Limestone Injection, FGD Sorbent Handling	kWe/(kg/s sorbent flow rate)	20
ASU	kWh/ton O_2	230
Fabric Filter Ash handling	kWe/kg/s	106.3
Amine Capture Auxiliary	kWe/(mol/s CO_2 entering vessel)	5.3411
Amine Capture CO_2 Compression	kWe/mol/s CO_2 captured	13.08
Oxygen-fired CO_2 Compression	kWe/ mol/s CO_2 captured	19.49

Case 1 Air-fired CFB power plant without CO_2 capture
Case 2 Oxy-CFB with CO_2 capture
Case 3 Air-fired CFB power plant with post-combustion amine-based CO_2 capture

2.2.1 Technical and Economic Analysis

The model is applied to scale cost and performance (loads, cost and emission values) with plant capacity and is used for the preliminary design. The published reports, which are simulated by ASPEN Plus® models, are used as base cases in the model [13][33][34]. 'Quality Guidelines for Energy Studies Cost Estimation Methodology for NETL Assessment of Power Plant Performance'' is accepted as cost estimation methodology [35]. A nominal (current)-dollar DCF analysis tool is used to compute the COE, LCOE and CO_2 capture cost [36].

The boiler parameters and load factors are taken directly from published reports [37] are shown in Table 2. Steam conditions of the Supercritical CFB are accepted as 24.1 MPa/593ºC/593ºC.

The oxy-CFB power plant applies the same environmental control techniques as the air-fired CFB plant. As an exception, Selective Non-Catalytic Reduction (SNCR) is not used for the oxy-CFB power plant. Cyclone and baghouse used for particulate emission control. According to coal S content, limestone injection method, spray dryer absorber (SDA) system or Dry - Wet FGD unit can be used for SOx control [13].

As environmental control techniques, fabric filter and dry flue gas desulphurisation unit (FGD) is selected due to the compliance to oxy-CFB technology. The in-bed limestone injection and flue gas desulfurization (FGD) unit can be used for SOx control in CFB. The in-bed limestone injection can be enough for low-S content coals. However, extra FGD unit might be needed for high-S content coals. [13] Orhaneli lignite is high-S content coal (S>1,5%). For this reason, the FGD system is used for SOx reduction in this study. SO_X removal efficiency of dry FGD is 93% [37].

The main properties of oxygen used in the oxy-fuel combustion generally at low pressure and purity. The oxygen pressure should be in the range of 1.3-1.7 bar and the oxygen purity should be in the range of 85-98% O_2 [38]. One of the most significant agents defining the power consumption of ASU is O_2 purity. The purity of O_2 indirectly affects the purity of CO_2 [23]. In this study, oxygen purity is 95% and its pressure is 0.1 MPa.

3.RESULTS AND DISCUSSIONS

3.1 Performance Summary

The performance values of the evaluated facilities are presented in Table 3. For three cases, same net electric power output (550 MWe) is accepted.

Adding ASU and CO_2 capture units resulted in an efficiency penalty in the system as expected. As seen in table 3, the amine-based process efficiency penalty is higher than the oxy-fuel combustion process. The efficiency penalty for oxy-CFB is 10% and for amine-based capture is 12%.

Studies have shown that oxy-combustion subsystems ASU and CPU cause a decrease of about 9-11% on the total plant efficiency. Most of this energy penalty

Table 3. Main Performance Summary of CFB power plants

Plant Data	Unit	case 1	case 2	case 3
Gross Power	MWe	578	801	678
Net Power	MWe	550	550	550
Net Plant Efficiency(HHV)	%	38%	28%	26%
Coal flowrate	t/day	7.541	10.229	11.230
Thermal Input	MWt	1439	1952	2143

HHV: High Heating Value

Table 4. CFB Cases Auxiliary Loads

AUXILIARY LOAD	Unit	case 1	case 2	case 3
Coal Handling	kWe	541	648	665
Pulverizer	kWe	157	213	222
Baghouse/ESP	kWe	258	377	365
Ash Handling	kWe	2.234	3.263	3.159
Primary/Forced Draft Fans	kWe	5.490	12.895	7.768
Induced Draft Fans	kWe	6.203	0	7.801
SNCR	kWe	13	0	19
FGD	kWe	323	484	458
FGD Sorbent Handling and Reagent Prep	kWe	384	499	551
Amine Capture Plus Auxiliaries	kWe	0	0	21.828
CO_2 Compression (2200psia)	kWe	0	75.771	48.102
ASU Compressor & Aux	kWe	0	138.878	0
Misc Balance of Plant	kWe	2.000	2.000	2.000
Turbine	kWe	400	400	400
Condensate Pumps	kWe	879	1.057	442
Water Pumps	kWe	2.658	4.868	8.981
Cooling Tower and Air-cooled Cond Fans	kWe	5.377	8.076	9.097
Transformer Losses	kWe	1.808	3.085	2.297
TOTAL AUXILIARIES		28.727	252.513	114.154

originate from ASU [23] [39]. Optimizing of ASU power consumption is extremely effective on the efficiency penalty. The efficiency penalty can be reduced by 3–7% in this way [40].

Matuszewski et al. searched the effect of ASU design on net plant energy efficiency. It was found that improving the heat integration in ASU design, total net energy efficiency could be increased by 8% [13].

Optimization and heat integration must be improved in the oxy-combustion to provide high overall system efficiency. It has been revealed that using waste heat from the ASU and CO_2 capture system to heat boiler feed water increases the energy efficiency of the overall system to a great extent [38].

The auxiliary loads of the designed facilities are shown in table 4. Fuel type, boiler type and ASU parameters are the factors affecting the auxiliary loads [13]. ASU and CO_2 Compression unit power density is remarkable in case 2. Also, the fan powers that enable flue gas recirculation are evident in case 2.

Table 5. CO_2 emission values and the specific CO_2 emission values

	CO_2 emission	kg/hr	kg/MWh net
Case 1	Stack	508	924
	Captured	0	0
Case 2	Stack	68.430	124
	Captured	615.866	1119
	Recycle	835.685	1519
Case 3	Stack	75.724	138
	Captured	681.518	1239

CO_2 emission values used for carbon capture calculations and the specific CO_2 emission values are shown in Table 5. Released CO_2 emission at case 1 is 924 kg/MWh net while the released CO_2 emission (stack) at case 2 is 124 kg/MWh net.

3.2. Economic Results

3.2.1. Estimation of Total Plant Cost

The capital costs are presented at the Total Plant Cost (TPC) level. TPC contains material & equipment cost, labour, engineering and constructing management cost [13] [37].

The costs are scaled for the same plant format by using different equations for the different subsystem. It uses at minimum one process parameter (flow rate, Capacity) by using an exponent which depends on equipment type. While equipment sizes grow, it becomes cheaper to increase extra capacity [37].

One of the most commonly used equation is Equation 1 as follows:

$$C_E = C_B \,.\, \left(\frac{Q}{QB}\right)^M \qquad (1)$$

C_E = Capital cost of the equipment with capacity Q

C_B= Capital cost of the equipment with capacity QB

M= exponent (0.6 is taken unless otherwise is specified)

The estimation of TPC is shown in Table 6. The highest costs of the three power plant facilities assessed are from the boiler, the steam turbine generator and the FGD. The cost of the SNCR is included in the cost of the CFB boiler in case 1 and case 3. Therefore, the cost of the SNCR is not shown separately.

In air-fired CFB (case 1), 39% of TPC is boiler cost, then comes the FGD with 13% of TPC and the steam turbine generator with 9.4% of TPC.

In oxy-fired CFB (case 2), the highest cost after the boiler belongs to ASU as expected. 16% of TPC is ASU cost, then comes the FGD with 7.5% of TPC and CO_2 capture unit with 5% of TPC.

In the future, reduction of oxygen production cost is the most important factor that will increase the competitiveness of oxy-fuel combustion technology

Table 6. Estimation of Total Plant Cost ($1MM= $1,000,000 USD) (2011 basis)

Sub-Systems		CASE 1	CASE 2	CASE 3
Boiler capital costs	MM$	491.663	584.497	630.712
Steamturbıne generator	MM$	118.452	148.800	135.998
Fuel handling/Prep	MM$	42.845	51.975	53.381
Feedwater&MiscBOP Systems	MM$	76.124	120.956	128.015
Dry FDG	MM$	167.193	147.190	215.082
Condenser	MM$	67.911	107.768	82.468
Coolıng water system	MM$	31.914	42.559	48.004
Ash-sorbent handling	MM$	30.655	37.903	37.231
Electrıc plant equipment	MM$	53.706	112.479	84.105
Instrumentatıon & control	MM$	22.894	30.241	27.318
Fabric filter	MM$	36.398	31.683	47.700
CO_2 capture	MM$	-	105.694	445.520
ASU	MM$	-	309.537	-
Buıldıngs& Structures	MM$	68.184	73.313	75.008
Ducting and Stack	MM$	40.703	29.803	44.634
Improvements to Site	MM$	14.671	16.069	16.270
Total		1.263.311	1.950.466	2.071.444

.

In this study, CO_2 purification unit is not designed. CO_2 pressure is 2200 psia for pipeline transport.

In the oxy-combustion process, the formed flue gas is less compared to the air-fired process. For this reason, the size of the boiler equipment (combustion chamber, cyclone, fabric filter, fans etc.) used becomes smaller. This also causes equipment cost savings of about 20% (in /kW-gross) [42].

The TPC showed a 54% increase in Case 2 compared to Case 1. The main reason for this cost increase percentage is the supplemented capture cost equipment. For capturing CO_2, oxy-boiler, ASU and gas processing units were added to the air-fired power plant [13].

The addition of a CO_2 capture plant showed a remarkable increase in total plant cost. This increase was much higher for post-combustion Amine-based CO_2 capture plant. TPC showed a 64% increase in Case 3 compared to Case 1. For the CO_2 capture process, the oxyfuel combustion process showed more advantageous results. Borgert and Rubin [27] found in their study that the oxy-fuel combustion process is cost-competitive or more low cost than the post-combustion process, especially for coals with low sulfur content.

In another study, it was found that the oxy-CFB plant's specific investment cost ($/kW net) was 80% higher than the air fired CFB plant with no CO_2 capture [42].

The costly subsystems of an oxy-combustion plant are ASU and CO_2 capture unit. These subsystems are more effective in the capital and operating costs than other subsystems.

The specific plant costs are calculated by considering plant cost and net generated power for each case. For oxy-CFB plant, the specific capital cost penalty is about 1250 $/kW net. Figure 4 presents the distribution of sub-systems to specific plant costs.

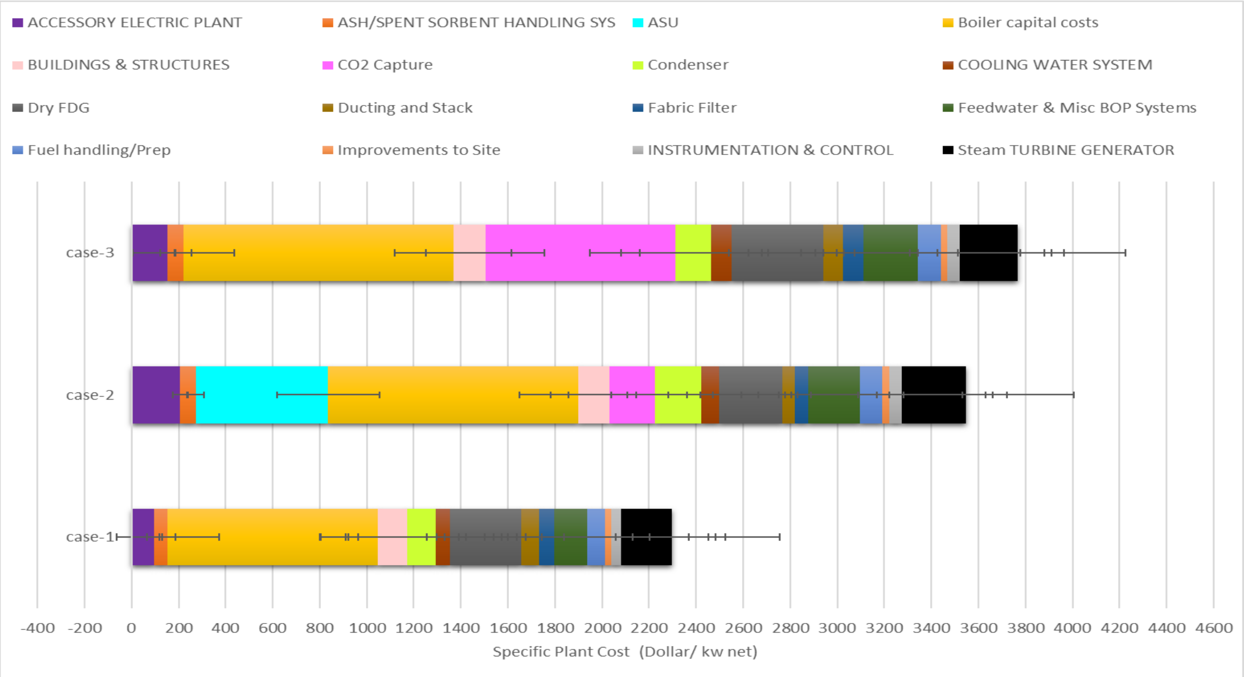

Figure 4. Distribution of sub-systems to Specific Plant Costs

3.2.2. Operation and Maintenance (O&M) Cost

O&M costs are separated as fixed and variable costs. Variable operating costs depend on the amount of power produced. Fixed costs are independent of the amount of power generated [16]. The fixed O&M labour cost accounts for the cost of labour, administrative cost, maintenance labour, and taxes and is independent of the power plant output.

Variable operating cost is the sum of maintenance material cost and cost of consumables (except fuel). The material cost is calculated as the yearly cost by multiplying the daily usage, unit cost, and the number of days per year in the plant operated. The number of operating days is determined by multiplying 365 days by the capacity factor [37]. The capacity factor is taken 0.85 and Turkish markets prices are used to calculate utility costs.

The distribution of O&M ($/kWh) costs is shown in Figure 5. The oxy-CFB O&M cost is 49.6% higher than the air-fired CFB. When case 2 compared to case 3, amine-based capture plant O&M cost is 9.6% higher than the oxy-CFB plant. The reason for this increase is the cost of the chemicals used in the amine-based system.

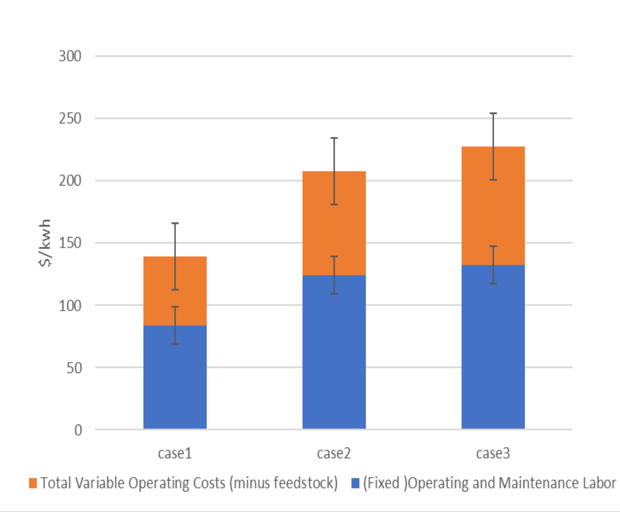

Figure 5. Distribution of O&M costs ($/kWh)

Variable O & M costs contain all consumable items (except fuel). The economic assumptions for calculating of the O&M costs are shown in Table7. No carbon tax is considered. The municipal water usage is 50% and the ground-water usage is 100% of the remaining water use. The estimated plant cost is updated according to by adjusting the data using CEPCI [41]. All Capital and Financing Costs are updated to values in 2015.

3.2.3 COE, LCOE and cost of CO_2 capture

COE is the power plants revenue per net MWh in the first operational year. "If the COE escalates thereafter at a nominal annual rate equal to the general inflation rate, i.e., that it remains constant in real terms over the operational period of the power plant. To calculate COE, the model can be used to determine a base-year COE that, when escalated at an assumed nominal annual general inflation rate of 3%, provides the stipulated Internal Rate of Return on Equity (IRROE) over the entire economic analysis period (capital expenditure period plus 30 years of operation)" [36] [44].

Table 7. O&M economic assumptions [31],[37],[43]

Operating & Maintenance Labor	
Labor Rate	30 $/hr
Labor Burden	25%
Overhead Charge	15%
Consumables	
Water	1,67($/gal)
Chemicals	
Limestone	15 $/ton
Calcium oxide	80 $/ton
MEA Solvent	3481 $/ton
NaOH for amine capture	671 $/ton
H_2SO_4 for amine capture	214 $/ton
Ammonia - 19% NH_3	330 $/ton
DeNOx Catalyst	8.938 $/ton
Waste Disposal	
ash	10 $/ton

The following equation (Equation 2) is used to estimate COE.

$$COE = \frac{\begin{matrix}\textit{first year} \\ \textit{capital charge}\end{matrix} + \begin{matrix}\textit{first year fixed} \\ \textit{operating costs}\end{matrix} + \begin{matrix}\textit{first year variable} \\ \textit{operating costs}\end{matrix}}{\textit{annual net megawatt hours generated}}$$

$$COE = \frac{\{CCF\}\{TOC\} + OC_{FIX} + \{CF\}\{OC_{VAR}\}}{\{CF\}\{MWH\}} \quad (2)$$

COE = cost of electricity generation (/MWh) throughout the power plant's first year of operation
CCF = capital charge factor
TOC = total overnight cost
OC_{FIX} = fixed operating costs
OC_{VAR}=variable operating costs,(including fuel)
CF = capacity factor

All parameters of the COE equation are expressed in base-year (the first year of capital expenditure) dollars. The parameters (COE, O&M, and fuel) escalated at a nominal yearly general inflation rate of 3.0% [36] [44]. The model calculates the base-year COE to calculate LCOE as defined above. Following, it multiplies the base-year COE by an end-of-year levelization factor (LF) that is a function of the defined IRROE and the general inflation rate that was performed to the COE [36]. LCOE consolidates capital costs, fuel costs, and (O&M) costs [45].

The cost of CO_2 captured is calculated using Equation 3. The carbon capture cost excludes transport and storage costs. The costs of CO_2 captured is calculated using Greenfield reference plants [35] [44].

$$Cost\ of\ CO_2\ Captured = \frac{\{COE_{withoutT\&S} - COE_{reference}\}\ \$/MWh}{\{CO_2\ Captured_{with\ removal}\}\ tonnes/MWh} \quad (3)$$

The COE, LCOE and CO_2 capture cost are shown in Table 8. The oxy-CFB plant COE value is 116 $/MWh. The COE showed a 52% increase in the oxy-CFB plant compared to air-fired CFB plant.

Table 8. The COE, LCOE and CO_2 capture cost

	Unit	case 1	case 2	case 3
First Year COE	($/MWh)	76	116	130
LCOE	($/MWh)	96	148	165
CO_2 capture cost	($/t)	-	35,7	43,58

It should be noted that owing to the decrease in net thermal efficiency, ASU energy consumption will influence the COE and the revenue generated from electricity sales [40].

The corresponding LCOE values for the case1 and case2 are 96 $/MWh and 148$/MWh respectively. This represents a 54% increase in LCOE when operating mode in the oxy-CFB. For the oxy-CFB plant, higher capital costs are the main cause of the increase in LCOE. Similarly, a 72% increase is observed for the amine-based plant.

The DOE has assigned targets supplying cost-effective electricity generation for advanced coal combustion technologies. This target is a maximum 35% increase in LCOE and at least 90% CO_2 capture [46]. In this study, 54% increase was obtained for LCOE. This increase is significantly greater than the DOE target.

The basic economic assumptions are shown in Table 9. In addition to global economic assumptions, in this study, Interest and tax rates, O&M sub-items (labour cost, consumables, etc.) is used according to TURKEY financial structure and market prices.

Rubin et al. (2015) evaluated CCS techno-economic studies which were performed in Europe and the USA. According to this study, the assumptions which were used for plant performance and costs were showed similarity. However, it is noted that fuel prices and price trends were very different between the US and Europe [45][47].

The quality of the coal used directly affects the performance and cost of the power plant. The coal calorific values determine the operating conditions of the boiler. If the heating value of the coal is not sufficient, it may be necessary adding to auxiliary combustion material to the boiler. The high sulfur content in the coal reduces the unit sulfur dioxide reduction cost of the desulfurization unit [32].

The differences in plant type and configuration, capacity factor, boiler type, coal type and price affect the result of economic performances. Since these factors may change the total plant costs, direct comparison of the data obtained in the literature may not give the correct result.

Table 9. Basic economic assumptions

Repayment Period	15 years
Capital Expenditure Term	5 Years
Operating life	30 years
Capital Cost Escalation	3.6%
Income Tax Rate	35% Effective
Depreciation Term	20 years
Working Capital	0
Escalation(COE,O&M,FuelCosts)	3%
Financial structure[a]	
Percentage Debt	45%
Percentage Equity	55%
Main financial assumptions	
Plant construction period(years)	5
Annual discount rate	8%[a]
Plant value at the end of operating life (M)	0%[a]
İnterest rate	5.5%
Orhaneli coal price $/Ton	30
Overall Capacity Factor	85%

a [16][26]

Therefore, the obtained values are compared on COE basis by the target of NETL. "Cost and Performance Baseline for Fossil Energy Power Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity 2014" is accepted as a basic study. The study contains the baselines of the economic indicators for SC-PC power plants both with and without carbon capture [48][49]. Figure 6 shows the comparison of the COE results of the proposed Oxy-CFB case and NETL studies.

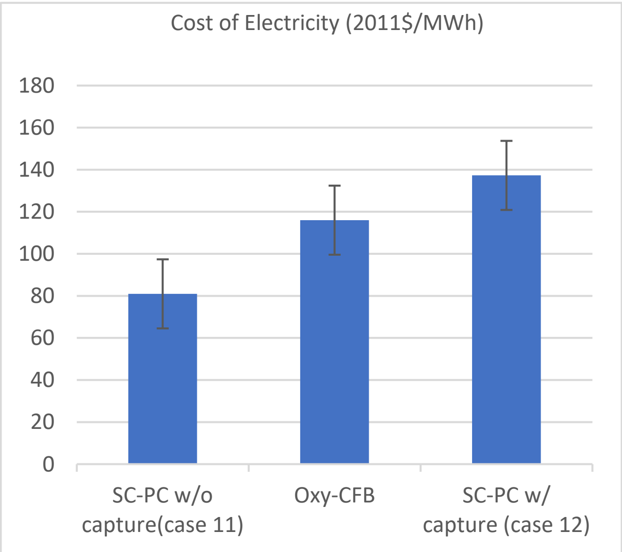

Figure 6. COE comparison of DOE (target) PC cases and oxy-CFB

Considering the COE, the designed oxy-CFB power plant is greater than the DOE target air-fired SC-PC (without capture) plant by 45%. It is remarkably lower than the amine-based SC-PC power plant.

M. van der Spek et. al [28] has presented the Techno-economic model for an ASC (advanced super-critic) PC oxyfuel plant generating 638 Mwe. In this study, oxy-combustion and amine-based CO_2 capture systems were used as a benchmark case. The study showed that ASC-PC oxyfuel plant has a net efficiency 2% point higher than amine-based CO_2 capture systems. But, economic performance indicators (CO_2 avoided cost, LCOE, and the capital costs) of the PC oxy-combustion plant is higher than the amine-based CO_2 capture systems. It was stated that improving performance may not be reflected in the cost of the system at all times and technologies are difficult to compare because of differences in design assumption and technology. As a result, it can be concluded that the best solution can be obtained for the project will be based on project-specific technology requirements.

Furthermore, The CO_2 capture cost in case2 (oxy-CFB) is lower compared to the case3 (amine-based capture system). The cost of CO_2 captured values are found to be 35.7 $ /ton for the oxy-CFB plant (case 2) and 43.58 $ /ton for the amine based CO2 capture systems (case 3) . The DOE has set a goal of reducing the cost of carbon capture to below the 40$/ton CO_2 by 2025 and reducing it to below 30$/ton CO_2 by 2035.[50]

4. CONCLUSION

The present study is performed to assess, the economic and technical model for an oxy-CFB plant generating 550 MWe with a CO_2 capture rate of 90% to be designed in TURKEY.

As a basic conclusion, the oxy-CFB plant has a lower plant cost, O&M cost, COE and LCOE, as well as lower efficiency penalty for CO_2 capture compared to amine-based carbon capture plant. The oxy-fuel combustion system is economically more advantageous than amine-based capture system.

The efficiency penalty for oxy-CFB is 10% and for amine-based capture, it is 12%. The performance of the amine-based capture is similar to oxyfuel performance. This difference can be offset by high costs of ASU, CO_2 compression, and amine capture units.

Plant size, capacity factor, total plant cost and the differences in coal type and price, affect the result of economic performances. The sensitivity analysis can be carried out to define the scopes for these effects.

As a result of the high equipment cost, ASU makes oxy-fuel plants less attractive. Likewise, ASU power requirement would impress the COE and the revenue from electricity sales. The development of ASU configuration will increase the plant viability in industrial applications. Improving thermal integration is known to ensure an important utility in terms of both efficiency and costs.

With the improvement of process design and thermal integration applications for future commercial applications, an oxy-power plant with carbon capture is a promising technology.

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Acronyms and abbreviations

ASU Air separation unit
CCS carbon capture and storage
CFB circulating fluidised bed
CPU carbon purification and compression unit
COE Cost of electricity
DOE US Department of Energy
FGD flue gas desulfurization
FGR flue gas recycle
GW GigaWatt
HHV higher heating value
IEA International Energy Agency
LCOE levelised cost of electricity
MEA Mono-ethanolamine
MWh megawatt hour
MWth megawatt thermal
MW Million Watt
NETL National Energy Technology Laboratory (USA)
OM Operation and maintenance cost
PC pulverised coal
SC supercritical
SNCR selective non-catalytic reduction
TPC total plant cost
TUBITAK Turkey Scientific and Technical Research Council of Turkey

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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