AMELIORATING TECHNOLOGIES FOR THE REDUCTION OF GREENHOUSE GAS EMISSIONS IN LIGNITE POWER PLANTS

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ABSTRACT

The recorded increased emissions of Green House Gases (GHGs), with electricity production having a key role to this increase, are bound to impact the anthropogenic and natural environment as well as jeopardize the world's sustainable development. The European Union's response to climate resilience and mitigation promotes, among others, decarbonization actions, i.e. replacement of coal plant-based units by greener technologies. This research paper explores the economic feasibility of modern technologies, such as i) improvements in the energy efficiency of fossil-fueled plants ii) carbon capture and storage, and iii) the combined combustion of biomass with lignite, with the aim of reducing GHGs emissions in a thermal lignite-based plant in Greece, planned to be decommissioned in the year 2028, and investigates its potentially prolonged operation until the year 2050. The evaluation of the proposed ameliorating technologies is conducted with the use of the Levelised Cost of Energy (LCOE) methodology. Hence, 15 scenarios related to advanced efficiency techniques, the gasification of lignite, carbon capture and storage, the replacement of lignite with natural gas and the combined combustion of biomass with lignite are examined. The results indicate that the Ultra Super Critical Pulverized Coal Combustion (USC-PCC) technology achieves the lowest LCOE since it coincides with an increased thermal efficiency of the power plant up to 49%. Despite their increased potential, the Integrated Gasification Combined Cycle (IGCC), Biomass Combustion and CSS technologies still have significant implementation costs. On the other hand, due to the uncertainty in the future prices of the natural gas, CCS may outweigh technologies that promote the use of natural gas to fuel the plant.

KEYWORDS

Ameliorating technologies; Carbon emission reduction; Climate change, Levelized cost of Electricity, Ptolemais V lignite plant

1. INTRODUCTION

It is beyond doubt that the planet's temperature, mainly due to the surge of Green House Gas (GHG) emissions, is gradually rising. The temperature increase coincides with several negative consequences, on people and the environment alike, thus directly threatening its sustainability in the forthcoming decades. Focusing on the Energy Sector, electricity production accounts for the 26.9% of

2018 GHG emissions, while approximately 63% of the world's electricity comes from the burning of fossil fuels[1]. Even though exceedingly ambitious targets have been proposed on a global scale in order to reduce the temperature rise below 1.5 ^{O}C, according to recent evidence the global GHG emissions emanating from anthropogenic activities, e.g. burning of fossil fuels, show little reduction[2].

Amongst the suggested approaches of the European Union in response to climate change and the mitigation of GHG emissions is decarbonization, i.e. the abolishment/replacement of coal plant-based thermal units by different technologies, for example renewables[3]. Greece, during the last few years and in accordance with the most recent national and European policies[4], has made a remarkable progress towards the reduction of fossil fuel dependency and the integration of renewable energy sources. Renewables may have reached technological maturity, but the involvement of back-up generation, energy storage, expanded transmission infrastructure, demand-side management, and energy curtailment may be required[5,6], thus affecting the total costs for further integration.

Regarding decarbonization, coal-fired power plants ensure the base load in various national grids, thus their abrupt withdrawal from the energy grid could increase the risk of national energy autonomy. On the other hand, the coverage of energy demands by coal of very low calorific value, i.e. the case of the Greek lignite, signifies increased lignite combustion to achieve the required efficiency; an issue which coincides with the release of significant amount of carbon dioxide to the atmosphere per unit of energy generated[7]. Hence, the need for investing on cleaner and ameliorating solutions for lignite plants becomes apparent.

The technologies for the improvement of energy efficiency of fossil-fueled power plants can be divided in the following categories: i) "Clean coal" technologies (CCT) that improve the efficiency rate of the power plant[8], ii) carbon capture and storage (CCS)[9], iii) fuel replacement, i.e. from coal to natural gas[10], and iv) co-firing biomass with coal[11]. Regarding CCT, the technologies that stand out are those of Ultra-Supercritical Combustion (USC), where efficiency rate is achieved by an increase in temperature and pressure conditions, and of Intergraded Gasification Combined Cycle (IGCC), where the increase of the net efficiency is achieved by the gasification of coal[12]. As for CCS technologies, they are considered important assets for the reduction of GHG emissions in the near future[9]. Finally, the co-firing of biomass with lignite, despite the technological barriers and the high cost, seems to be a promising and greener solution.

The aim of the research is to assess specific CCT, CCS, fuel replacement and the co-firing of biomass with lignite technologies in the framework of investigating their economic feasibility. The case study area is the lignite-firing power plant of Ptolemais V in Greece, which under the recent decarbonization program of the National Plan for Energy and Climate, is scheduled to stop operating with lignite as a base fuel in 2028. The second section presents the applied methodology for comparing the various technologies as well as the developed scenarios. The results and their discussion are included in the third section, which is followed by the conclusions of the conducted research.

2. METHODOLOGY

Ptolemais V is a power plant unit, still under construction and it is located 8 km outside the city of Ptolemais in the Region of Western Macedonia in Greece. Its estimated power capacity is 660MW. The station's main fuel is pulverized lignite, extracted from lignite mines in the same area. The net-efficiency of the thermal unit is approximately 41.5% and the emission rate of CO_2 is 1.04 Kg/KWh. The super-critical conditions of the unit are 250 bar/600°C/609°C. The unit's design has also predicted areas of possible Carbon Capture installation. The project's cost has reached €1.4 billion[13].

For the evaluation of the proposed ameliorating technologies in the plant under study, the Levelized Cost of Electricity (LCOE) has been implemented. LCOE is a lifecycle cost analysis of a power plant that uses assumptions about the future value of money to convert all future costs and revenues into current prices[14]. This model is widely used in the power industry but has some significant failings, particularly in its ability to handle risk. LCOE is widely used for the comparison of different methods for energy generation on a comparable basis[14], and calculates the weighted cost (in €/MWh) of electricity generation during a production unit's lifetime, expressed in present values, according to the following equation:

$$LCOE = \frac{\sum_{t=1}^{n}[(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) * (1+r)^{-t}]}{\sum_{t=1}^{n}[MWh * (1+r)^{-t}]}$$

where $Capital_t$ are the investment costs, $O\&M_t$ the operational and maintenance costs, $Fuel_t$ the costs of the fuels (lignite, gas and biomass), $Carbon_t$ the emissions cost, D_t the decommissioning cost, expressed in time t; r is the rate of return (discount rate) and n is a project's lifetime.

To that end, fifteen (15) scenarios related to advanced efficiency technologies, CCS, gasification of lignite, replacement of lignite with natural gas and combined combustion of biomass with lignite are examined. The first 11 proposed solutions assume that the unit is constructed ab initio and will operate until 2050. The four remaining cases presuppose that during the de-carbonization year (2028), the unit will either switch to natural gas or to co-firing lignite with biomass or a CCS technology will be implemented. The proposed scenarios are the following:

Case 1 (SP-PC) Current condition- Super critical Pulverized lignite of 660MW.

Case 2 SCPL-CCS Construction of a new power plant with super critical pulverized lignite as a fuel and CCS installation.

Case 3 USC-PL Construction of a new power plant with Ultra-super critical pulverized lignite as a fuel.

Case 4 USC-PC-CCS Construction of a new power plant with Ultra-super critical pulverized lignite as a fuel with CCS installation.

Case 5 (IGCC) *Construction* of a new power plant with Integrated Gasification Combined Cycle.

Case 6. (IGCC-CCS) Construction of a new power plant with Integrated Gasification Combined Cycle and CCS.

Case 7 (CCGT) Construction of a new power plant with natural gas as fossil fuel in a Combined Cycle Gas Turbine.

Case 8 (A-CCGT) Construction of a new power plant of Advanced-Combined Cycle Gas Turbine

Case 9 (A-CCGT-CCS) Construction of a new power plant of Advanced-Combined Cycle Gas Turbine with CCS

Case 10 (SCPC–BC10%) Construction of a new power plant of co-firing lignite and biomass (90%-10%)

Case 11 (SCPC–BC30%) Construction of a new power plant of co-firing lignite and biomass (70%-30%)

Case 12 (CT-CCGT2028) Conversion of the existing power plant to a natural gas-firing plant in the year 2028.

Case 13 (CT-SCPC-CCS2028) Conversion of the existing power plant to a super-critical pulverized lignite with CCS in year 2028.

Case 14 (CT-SCPC BC 10% 2028) Conversion of the existing power plant to a co-firing unit of lignite and biomass (90%-10%) in the year 2028.

Case 15 (CT-SCPC BC 30% 2028) Conversion of the existing power plant to a co-firing unit of lignite and biomass (70%-30%) in the year 2028.

3. RESULTS AND DISCUSSION

The LCOE factor was calculated, having considered the correlation between the main parameters of capital cost, fixed cost, variable cost, maintenance cost, decommissioning cost, the projected evolution of natural gas prices and the projection of carbon emission prices, with the results to be demonstrated in Table 1. All of the above were calculated with 3 different discount rates (3%, 7% and 10%) and with two different possible future developments of CO_2 emission allowance prices on the basis of the projected scenarios provided in the National Plan of Energy and Climate[15]. Additionally, LCOE considers the expected compensation given by the state, known as Power Availability Certificate (PAC), when the plant manages to hold emissions under the threshold of 0.56 $KgCO_2/MWh$. Finally, the capital cost for the current thermal plant was taken from the PCC techno-economic Report. The capital costs for the rest of the cases were selected from bibliographical references[16].

Table 1. *Cumulative results of each suggested thermal unit including efficiency, emission rate, capital cost, emission cost, fuel cost and LCOE.*

Power Plant	*Efficiency*	*Emission rate ($KgCO_2/MWh$)*	*Capital cost (€/KW)*	*Emission cost (€)*	*Fuel cost (€)*	*LCOE(€/MWh)*
SCPC	41.5	1.05	2106	6,908,988,240	3,086,726,344	**98.00**
SPC-CCS	32	0.1	3272	690,898,824	4,003,098,037	**122.00**
USC-PC	49	0.7	3580	4,605,992,160	2,614,268,060	**94.74**
USC-PC-CCS	41	0.07	4023	460,599,216	3,202,478,306	**113.92**
IGCC	48	0.83	3593	5,474,550,682	2,668,732,050	**110.00**
IGCC-CCS	40	0.08	5483	547,455,068	3,124,369,239	**123.00**
CT-SPCCS (2028)	32	0.1	2857	1,563,729,552	3,781,904,870	**106.36**
CCGT	58	0.56	880	3,750,593,616	8,821,996,725	**100.30**
ACCG	60	0.33	993	4,605,992,160	10,378,819,676	**101.32**
ACCG-CCS	51	0.03	1885	460,599,216	10,032,859,020	**116.36**
CT-CCNG (2028)	58	0.56	2556	1,563,729,552	8,821,996,725	**108.41**
SCPC –BC 10%	29	0.945	3016	6,218,089,416	3,807,239,973	**112.93**
SCPC –BC 30%	29	0.735	3016	4,836,291,768	5,457,254,904	**116.92**
CT- SCPC BC 10%	29	0.98	3016	6,350,114,232	3,019,535,151	**116.27**
CT- SCPC BC 30%	29	0.7	3016	4,836,291,768	4,139,986,479	**115.68**

3.1 Overview of LCOE cumulative results

As illustrated in Figure 1, the biggest reduction in the LCOE factor is accomplished by the USC technology. This result highlights the importance of a high efficiency rate, as a 7% increase of the net efficiency results to a 15% reduction in emission cost. Unfortunately, the capital cost of this technology remains high since the demands of very high quality and rare alloys for the plant's pipeline are still prohibitive.

Another aspect of the biomass scenarios, even though they seem environmentally friendlier and come with a relatively lower overnight cost, is that they result in a disproportionate increase on the fuel price of biomass due to the large amounts of biomass that need to be transferred or be cultivated.

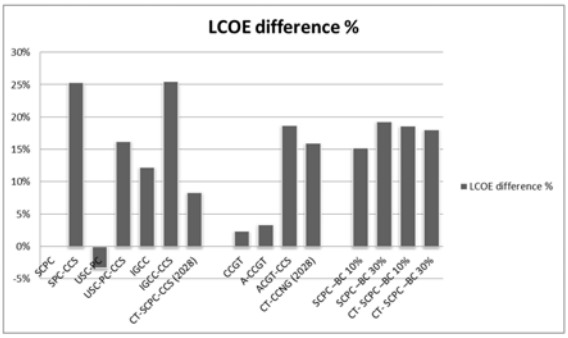

Figure 1. Percentages of LCOE increase of different technologies in comparison with the current case.

Upon the scenarios where a conversion takes places in 2028, Figure 2 demonstrates that CCS technology has the lowest LCOE. From a financial point of view, the cost increase of CCS implementation will be slightly smaller than the cost of converting the plant to gas-firing. Moreover, CCS implementation is preferable due to compatibility issues. A super-critical boiler is already designed to burn the available type of lignite, so in the opposite case of switching from lignite to gas, an undetermined cost of malfunction should be expected.

An additional reason that underpins the ambiguity of a natural gas-firing power station, despite the low capital cost and the historical low prices in the year 2020, is the inherent uncertainty that imported fuel prices bear, resulting to the uncertainty of electricity prices. On the contrary, the lignite domestic market is practically independent on oil prices, which significantly annihilates the risk factor in relation to cost assessment. The variation in the risk of gas price is clearly greater than the risk of CCS implementation.

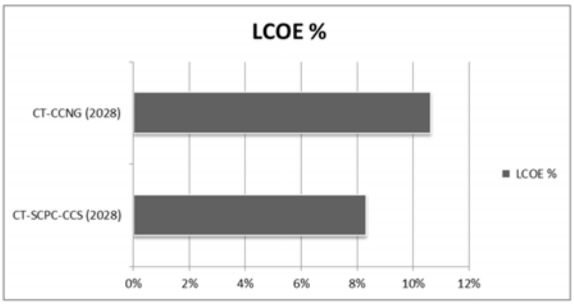

Figure 2 Percentage comparison of LCOE increase between the CCS installation and the conversion to gas-firing in 2028.

3.1 Modification of parameters

The correlation of LCOE when the discount rate is modified is illustrated in Figure 3 for the first developed scenario, i.e. Case 1. The three discount rates that were selected (0.03, 0.07, 0.1) indicated that LCOE is increasing in proportion to the rise of the discount rate.

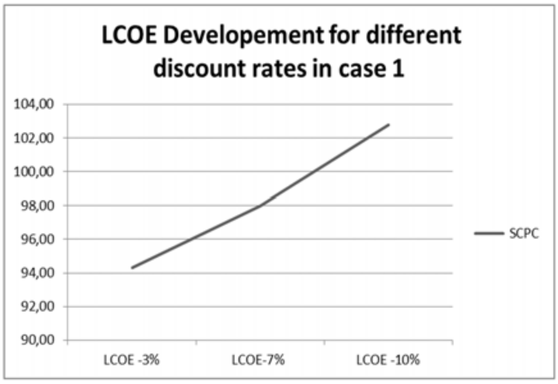

Figure 3. Development of LCOE according to three different discount rates.

The modification of the LCOE factor, when future emission prices are altered, is depicted in Figure 4. Adopting a moderate (88.0 €/tCO_2) and an extreme (380.0 €/tCO_2) scenario of future CO_2 emission prices for the year 2050[15], the results indicate that LCOE increase to the point the thermal stations are no longer viable, with the exception of those attributed with CCS technology. The reason behind this is that CSS technology is designed to capture 90% of CO_2, with this issue being an additional advantage of the specific technology.

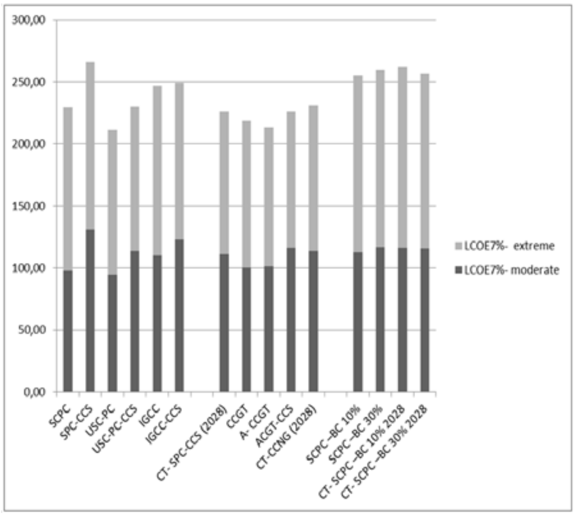

Figure 4. LCOE comparison of different technologies in accordance with two CO_2 emissions development prices.

It should also be stated that all the aforementioned calculations have been made under the assumption that energy demand remains the same over the years of utilization. Thus, the LCOE analysis is not capable of assessing accurately the economic viability of thermal plants. A more thorough study, which is planned for the further development of the research, should take into consideration the evolution of the load curve of the thermal plant that derived from the prediction of energy demand. This process gives priority to the penetration percentage of renewables, which further undervalues the contribution of thermal plants. The research of WWF Hellas [17] on that matter shows that as the energy demand in power plants fades, the economic capabilities of the unit are further confined. The LCOE equation also emphatically shows that as the power demand is declining, the LCOE factor is rising.

4. CONCLUSIONS

In the research, the Ultra Super Critical Pulverized Coal Combustion (USC-PCC) technology presents the lower LCOE since it coincides with an increased thermal efficiency of the power plant up to 49%. The results also suggest that high efficiency power plants up to 48- 49% can ensure greener and economically expedient solutions. Other technologies such as IGCC and biomass co-firing, despite their potential benefits, are still significantly expensive. However, due to uncertainties on the natural gas future prices and other operational parameters, CCS may have benefits against technologies that promote conversion of the plant to gas-firing technologies.

Regarding the implementation of CCS in Ptolemais V, a modern lignite power plant is expected to lose from 7.4% to 11.8% of its efficiency while the price of electricity is increasing by 47%-65%. The Post-Combustion Capture has prospects of successful implementation in Greek thermal plants. Finally, the total cost of the plant is expected to be further decreased when the threshold of minimum emissions is achieved, i.e. the PAC compensations can contribute to the economic feasibility of the unit. Thus, the cost of electricity is expected to rise only by 15%-18%. As far as biomass co-firing technologies are concerned, it is also worth mentioning that this technology bears few unexcelled technical restrictions, particularly for large thermal power plants and concerns the proper mixture co-burning analogy greater than 20% biomass-80% Lignite[18].

To sum up, the abrupt withdrawal of lignite plant-based thermal units from the national grid reduces national energy autonomy[19]. On the other hand, electricity production by lignite-based power plants is unsustainable. Therefore, alternative ameliorating technological solutions, such as those investigated in the research paper, could provide a smoother transition to a zero-emission future.

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