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Economic evaluation of A-USC power plant with CO_2 capture unit

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Abstract

Achieving CO_2 emission control while keeping electricity prices competitive is a key economic and technical challenge. The strategy for lowering CO_2 emission from coal-based power plants includes primarily raising electricity generation efficiency. Currently, steam temperatures in ultra-supercritical (USC) power plants are limited to approximately 627°C by the use of the most advanced commercially available ferritic steels. To go to higher temperatures, high-nickel alloys must be used. Nickel alloys are at an advanced stage of development and are expected to become available to support the construction of a demonstration plant in Europe in 2021. For pulverized coal (PC) plants nickel alloy development means progressing to advanced ultra-supercritical (A-USC) steam conditions: 35 MPa/700/720°C. The concept consists of gradually raising the live steam temperature and pressure, but it can become economically unjustified. The cost-effectiveness of new investments can be provided only through a significant increase in the efficiency of electricity generation. In this paper the economic evaluation of a 900 MW PC unit is presented. The main aim is to compare the cost of electricity generation in USC (28 MPa/600/620°C) and A-USC (35 MPa/700/720°C) power units. Variants with CO_2 capture installation by chemical absorption MEA are considered. Compared to a USC design, the capital cost of the A-USC PC plant will be higher, but the operating cost lower. Owing to the higher efficiency of the A-USC plant, the differential in terms of operating cost increases as fuel price increases and CO_2 cost charges are included.

Keywords: Keywords: A-USC power plant, PC power plant, CO_2 capture

1. Introduction

Coal-based units are a key ingredient in the power generation mix. Pulverized coal plants enjoy the lowest electricity production costs the most proven technology. The need to reduce greenhouse gas emissions and improve the economics of electricity generation have resulted in significant progress in the field of condensing coal-fired power plants. The development of coal technology is currently focused on achieving higher efficiency with the objectives being to reduce fuel consumption and CO_2 emissions (Fig. 1). A great step forward in the field of materials engineering led to implementation of ultra-supercritical (USC) power plants with steam temperatures

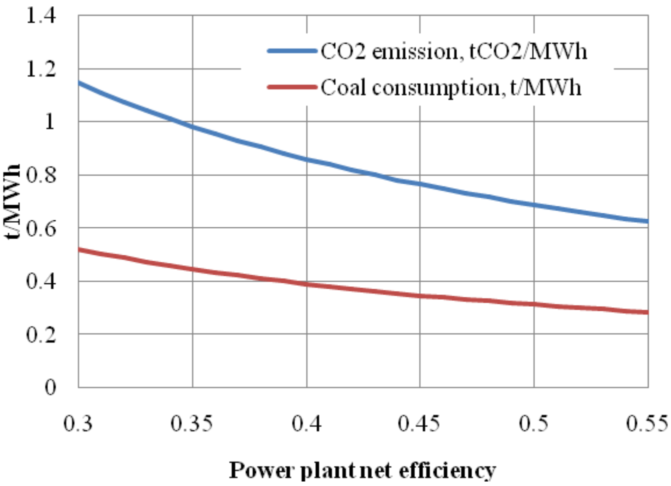

Figure 1: Specific CO_2 emission and coal consumption per MWh as a function of power plant net efficiency (hard coal: LHV=23 MJ/kg, C=60%)

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of 600/620°C. The European reference standard determines a conceptual coal-fired power plant thus: Reference Power Plant Parameters with steam parameters of 28.5 MPa/600/620°C. Power unit achieves net efficiency of 45.9% with pressure in the condenser of 4.5 kPa [1].

The power industry around the world has set itself an ambitious goal: to advance net efficiency of coal-fired units from the current reference value of 46% to 50% and higher. Passing the symbolic barrier of 50% will require significant changes in technology and in particular major progress in the field of the materials engineering. Increasing the steam temperature above 620°C requires the use of new materials based on nickel. The huge costs associated with the use of nickel alloys in the key elements of the power unit drove a huge step forward in the upper parameters of the steam cycle and the start of the next phase of development—power plant with advanced ultra-supercritical parameters (A-USC). It transpired that the concept consisting in gradually raising the steam temperature and pressure can become economically unjustified. The cost-effectiveness of new investments can be achieved only through a significant increase in the efficiency of electricity generation. For this reason, the main development objective of the power industry in Europe became live steam temperature of 700°C and pressure up to 35 MPa.

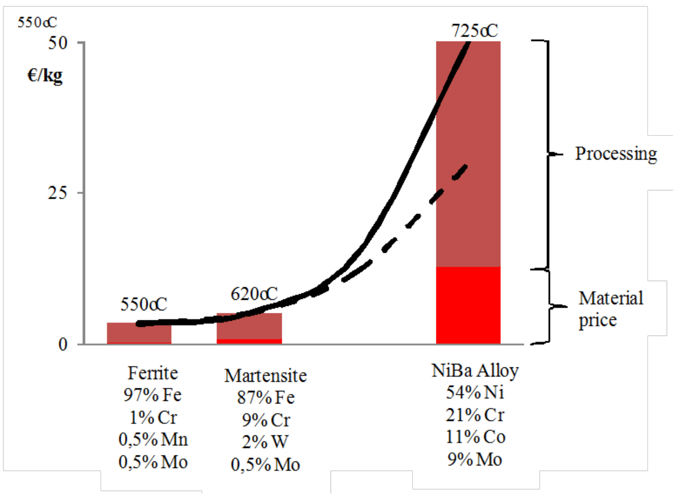

Figure 2: Material costs increase

The increase in efficiency is proportional to the rise in steam temperature. In contrast, the price of materials increases exponentially relative to steam temperature (Fig. 2). Additional costs result from extra processing of the material, such as stamping or milling. These costs are much higher than they are with conventional steels due to the technologically advanced treatment of nickel alloys. The very high costs associated with the development of A-USC technology and the construction of a demo power plant led to the initiation of many wide-ranging research and development programs at the European and global level (Table 1). The commissioning of an A-USC demonstration plant in Europe and one in the USA is scheduled for 2021. It is expected that A-USC power plants will be commercially available after 2026, and A-USC with CCS—after 2031 (Table 2).

2. Plant description

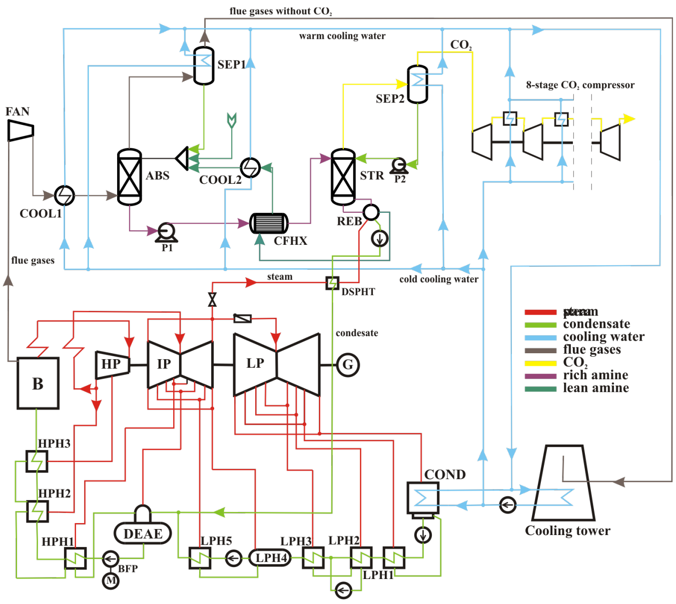

Figure 3: Diagram of an A-USC power plant integrated with a CO_2 capture unit (CCU)

The subject of the study was a conceptual A USC coal-fired power plant integrated with a CO_2 capture and compression unit (CCU) (Fig. 3). Due to the state of the art of CO_2 capture methods and the ability of their application to the high power unit, the post-combustion method by wet chemical absorption MEA is taken into consideration [3]. The live and reheated steam parameters of conceptual A-USC are 35 MPa/700°C and 7.5 MPa/720°C, respectively. The power unit under analysis is fired with hard coal with a lower heating value of 23 MJ/kg. The final feed water temperature is 330°C. The calculations take into account the demand for electric power of the power unit's basic own-needs equipment (the boiler feed pump, the condensate pumps, the cooling water pumps, the air and flue gas fans, and the coal pulverizers) as well as of the CO_2 capture and compression installation (pumps, fans, CO_2 compressor). All own-needs devices have an electric drive. The steam for the sorbent regeneration is extracted from the main turbine IP/LP crossover pipe. The temperature difference in reboiler REB between the condensing steam fed from the power unit thermal cycle and the heated MEA solution is 10K. The required minimum parameters of the steam feeding the reboiler are as follows: 0.33 MPa and 134°C. The reboiler feed steam condensate is returned and introduced into the cycle in the low-pressure regeneration region. The entire heat flux resulting from the cooling of the turbine condenser, the CO_2 capture installation, power unit auxiliary equipment and the CO_2 compressor interstage coolers is given up in the cooling tower. The CO_2 capture and compression process was modelled in the Aspen PLUS program and was used to determine basic indices, including the demand for cooling water. These indices were used as input data to the model of the coal-fired condensing power unit. This made it possible to define the impact of integration on the basic indices of unit operation. The Ebsilon Professional 10.0 software package was used for the analysis of the operation of the power unit integrated with a CO_2 capture unit. The coal-fired power plant was modeled with the flue gas duct and the cooling water system together with a cooling tower with natural draught. The CO_2 capture and compression installation was taken into account in the power unit calculations in the form of characteristics developed based on the calculation results obtained for the chemical absorption model in the Aspen PLUS.

Table 3: Characteristics of CO_2 capture unit (CCU) by wet chemical absorption

Solvent	30% MEA solution
Capture rate	90%
Regeneration (reboiler) temperature	124°C
Specific heat duty	3.51 $MJ_{th}/kgCO_2$
Specific cooling duty (with CO_2 compressor)	3.76 $MJ_{th}/kgCO_2$
Specific power duty (with CO_2 compressor)	0.44 $MW_e/kgCO_2$
CO_2 pressure after compression	15.3 MPa (abs)

CO_2 capture by wet chemical absorption is related with high unit efficiency and power penalties. Efficiency losses occur due to the high heat demand to regenerate the solvent and the power demand to compress CO_2. The efficiencies of power plants with CO_2 capture based on the current leading technologies are 32...35%, LHV basis for hard coal fired plants [4]. The characteristics of a CO_2 capture unit (CCU) by wet chemical absorption are presented in Table 3. The plant integrated with CCU has the net electric power of 642.93 MW and net efficiency of 37.58%. Assuming identical live steam mass flow of 578.4 kg/s, the power plant without CCU achieves net electric power of 838.9 MW and electricity generation efficiency of 49.04%. The plant configuration assumed in the analysis was developed in previous analyzes described in [5–9].

The conceptual A-USC power unit is compared with a reference USC unit with steam parameters of 28.5 MPa/600/620°C. The structure of the unit is presented in [1]. Plants with these steam conditions are commercially available and plants with similar conditions are being built and operated in Europe and Japan. The calculated net efficiency of the USC unit is 46.29% and is higher than the reference of 46% [1]. This results from differences in the adopted assumption. However, it must be emphasized that identical assumptions were adopted when analyzing the A-USC and USC power plants. The basic operating indices of the USC and A-USC power units are listed in Table 4.

The factors which contribute to the efficiency reductions for CO_2 capture for each fuel and technology are summarized in Fig. 4. For post-combustion capture, more than half of the efficiency reduction is due to the use of low-pressure steam for CO_2 capture solvent regeneration. The second factor reducing efficiency is the CO_2 compressor power demand. Other power and efficiency penalties result from the CCU auxiliary equipment power demand and the higher power to drive the cooling water pumps.

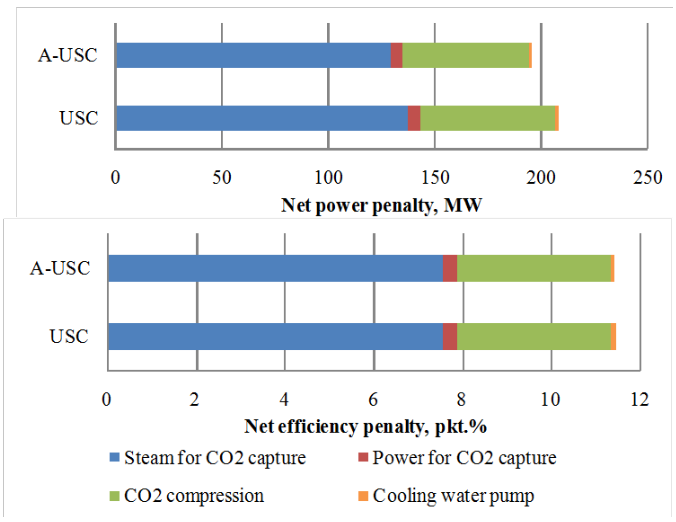

Figure 4: Breakdown of power and efficiency penalty for CO_2 capture in USC and A-USC power plant

3. Economic comparison of USC and A-USC power plant

3.1. NPV analysis

The economic analysis of the coal-fired power unit was based on the net present value—NPV—method according to [10]. NPV is defined by the following formula:

$$NPV = \sum_{t=1}^{t=N} \frac{CF_t}{(1+r)^t} \tag{1}$$

where: CFt—cash flows in time t, r—discount rate, t—next year of consideration from the commencement of the unit construction.

Discount rate r is calculated from the following formula:

$$r = r_k(1-p_d)u_k + r_w(1-u_k) \tag{2}$$

where: r_k—commercial credit rate, p_d—income tax, u_k—share of credit in the investment financing, rw—return on equity.

Commercial credit rate is calculated from the formula:

$$r_k = \frac{WIBOR - i}{1+i} + m \tag{3}$$

where: i—inflation, m—margin.

Cash flows in time t are defined by the following dependence:

$$CF_t = [-J + S_{el} - (K_{op} + P_d + K_{obr}) + A + L \tag{4}$$

where: J—investment expenditures, S_{el}—revenues from the sale of electricity, K_{op}—operating costs, P_d—income tax, in the working capital, A —depreciation, L—liquidation value.

Revenues from the sale of electricity:

$$S_{el} = \int_0^{\tau} N_{elN} C_{el} d\tau \tag{5}$$

where: N_{elN}—the unit net power, C_{el}—average selling price of electricity, τ—total annual operation time of the power unit.

Operating costs:

$$K_{op} = K_f + K_o + K_{ps} + K_e + K_r + K_u + A_k + A \tag{6}$$

where: K_f—fuel costs, K_r—servicing, maintenance and repair costs.

It was assumed that the service life of the power unit was 20 years. The construction of the power unit was spread over 4 years, and the allocation of investment funds in each year was 10, 25, 35 and 30%, respectively. Additionally, the liquidation value of the investment was omitted in the calculations of the NPV. It was additionally assumed that the costs of repairs and insurance are constant and each year they are equal to 1% of the investment costs. The average exchange rate of 1 US dollar in the previous three months was assumed at 3.03 zlotys. The economic analysis also included the costs of emissions of sulfur and nitrogen oxides ($140 per metric ton), and carbon dioxide. Moreover, many extra fixed and variable costs were taken into account, such as the cost of disposal of solid products, lime suspension costs and the cost of demineralized water.

3.2. Investment costs

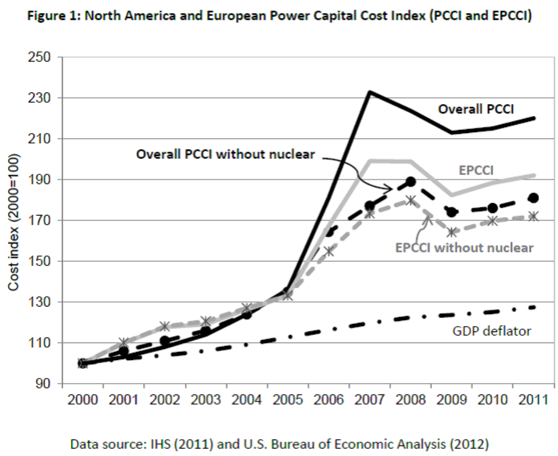

Figure 5: PCCI (North America Power Capital Cost Index) and EPCCI (European Power Capital Cost Index) (GDP deflator) [11]

Table 5: Comparison of investment costs for four types of coal-fired 750 MW power units

Steam parameters	Investment costs $/kW
Subcritical	1,780
Supercritical (SC)	1,800
Ultra–supercritical (USC)	1,840
Advanced ultra–supercritical (A–USC)	2,090

In recent years capital costs for power units in developed countries have grown three times faster than inflation. This trend looks set to continue in the future [13]. A decade ago, it was anticipated that the investment costs for advanced coal-fired units would fall in line with the experience curve. Currently, the capital cost of a coal-fired

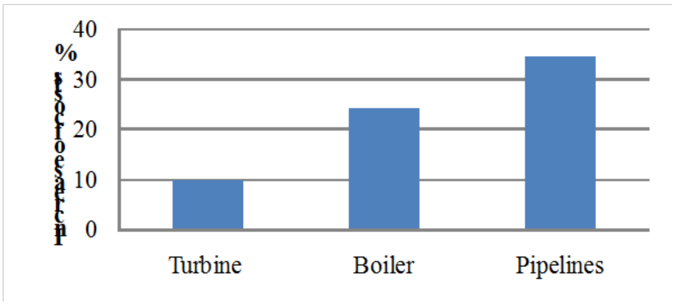

Figure 6: Increase of turbine, boiler and pipelines costs in A-USC power unit compared to USC [12]

condensing power unit is \$1.3...2.2 million for 1 MW of installed power [14]. The power unit investment costs include [15]: cost of purchase of equipment, construction, infrastructure, labor, cost of design, cost of permits, pre-production costs and contingencies. Three factors play a major role in shaping the investment cost of the power unit: the price of materials (e.g. steel), local regulations (environmental regulations, state subsidies) and the cost of labor. Costs are also strongly related to the location of the investment. In recent years, a leader in the construction of supercritical power units is China, often offering a price one-half lower than European or American contractors. Fig. 5 shows the changes in two indicators of trends in plant costs in the power sector since 2000. The Power Capital Cost Index PCCI [11] shows the changes in power unit cost developed on the basis of 30 different units (coal, gas, nuclear, wind) in North America. In turn the European Power Capital Cost Index EPCCI [11] presents changes in unit costs in Europe. The significant increase in investment costs relative to the base year is mainly related to the increase in the prices of materials (steel, aluminum) and increased demand in the energy market. According to the EPRI economic evaluation presented in [12], the results of which are summarized in Table 5, A-USC power unit investment cost may reach \$2,090 per kW of installed power and will be about 13.5% higher than for a USC power unit. The A USC steam turbine cost will be about 10% higher than for a USC, boiler: 25% and pipelines: 35% (Fig. 6).

3.3. Operating costs

Fuel price is a major factor in electricity cost. For power generators coal is about one-half of all costs. The cost of hard coal is usually about 60...70% of all operating costs [14]. Currently, the price of hard coal for power plants is about \$4/GJ. The cost of reference coal (LHV=23 MJ/kg) is \$92.88/t. Currently, the CO_2 charge is low (about €5...7/t_{CO_2}). Four years ago this charge

Table 6: Assumptions for economic analysis

Fuel price	100 \$/t (60...160 \$/t)
CO_2 charge	50 \$/tCO_2 (0...100 \$/t_{CO_2})
USC investment cost	1840 \$/kW
A-USC investment cost	2090 \$/kW
CCU investment cost	1300 \$/kW
MEA solution cost	1300 \$/t
CO_2 transportation cost	7 \$/t_{CO_2}/100km
CO_2 storage cost	1,5\$/t_{CO_2}
Distance from power plant to storage area	100km

was €40/t_{CO_2}. In the case of a power unit integrated with a CO_2 capture installation it is also necessary to take into account the operating costs of the CCU and the costs of CO_2 transportation and storage. The power plants described above include compression of CO_2 to 15.3 MPa for pipeline transport and underground storage. The costs of transporting CO_2 from a power plant to a storage site and the costs of storage depend on local circumstances. Literature [16–19] gives very different data about the transportation and storage of CO_2. The costs depend largely on local conditions, especially the distance from the plant to the storage area and the specific storage capacity. Typically, American literature gives total costs of transportation and injection in the range of \$5...15 per metric ton of stored CO_2. Technical and economic studies conducted for the purposes of Polish units show that the cost of transportation in urban areas is approximately €5 per 100 km per metric ton of CO_2. The cost of storage is €0.6...1.1/t_{CO_2}. Estimated costs of CO_2 removal (capture, transportation and storage) per metric ton of CO_2 for the CCS project in Bełchatów Power Plant were €65...70/t_{CO_2} [20]. The assumptions for the economic analysis are summarized in Table 6.

3.4. Results

Fig. 7 presents a comparison of costs of electricity for six variants: USC with no CO_2 charge, USC with CO_2 charge, USC integrated with CCS and their counterparts for A-USC. Costs of electricity for the A-USC variant are higher than for the USC. This results from the much higher A-USC investment costs (fuel costs are lower). For variants with CO_2 charge and integration with CCS the A-USC variant has lower costs of electricity generation.

Fig. 8 shows costs of fuel in \$ per MWh of electricity as a function of fuel price compared to two variants of CO_2

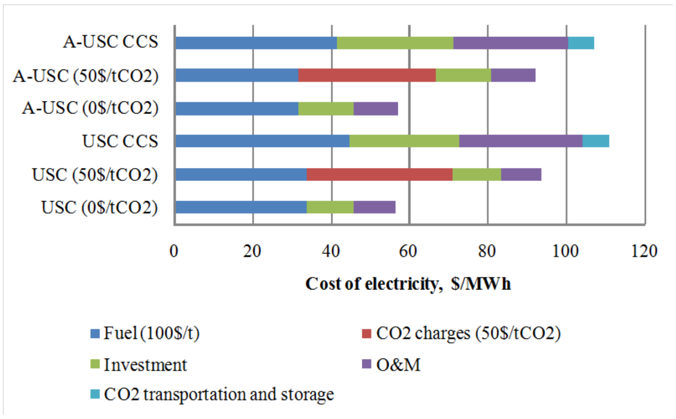

Figure 7: Breakdown of costs of electricty (fuel price: 100$/t, annual operating time: 8,000 h)

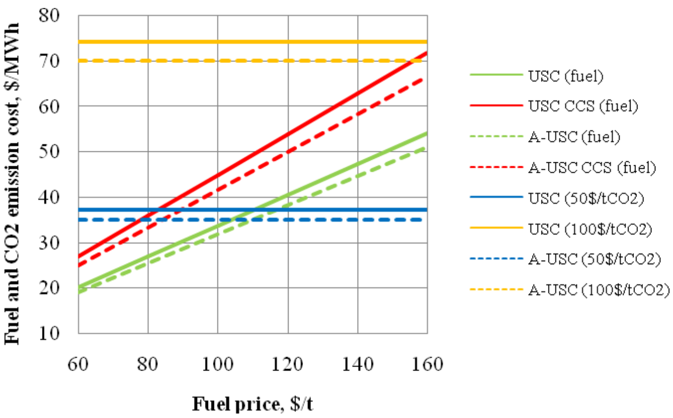

Figure 8: Fuel and CO_2 emission costs ($/MWh) as a function of fuel price for USC and A-USC power plants

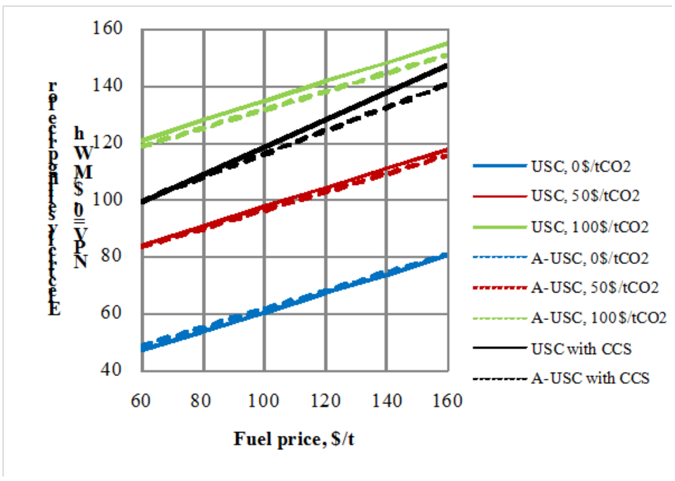

Figure 9: Electricity selling price (NPV=0) as a function of fuel price for USC and A-USC power plant for various CO_2 charges (0.50 and 100$/$t_{CO_2}$) and annual operating time of 8,000 h/year

charges of 50 and 100 $/t. The difference between USC and A-USC rises with the fuel price. Fig. 9 presents the electricity selling price, which was calculated for NPV=0

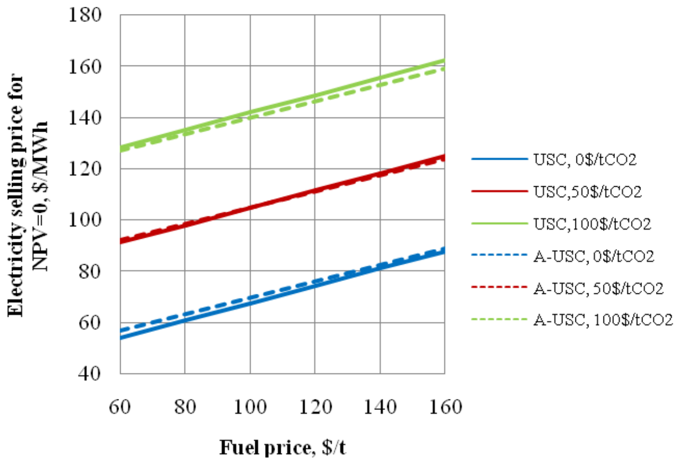

Figure 10: Elektricity selling price (NPV=0) as a function of fuel price for USC and A-USC power plant for various CO_2 charges (0.50 and 100$/$t_{CO_2}$) and annual operating time of 6,000 h/year

and the annual operating time of 8,000 h. Fig. 10 presets the electricity selling price for the NPV=0 and the annual operating time of 6,000 h. Variant A-USC (0 $/$t_{CO_2}$—Fig. 9) achieves a higher electricity price than USC over the range of the fuel price. A shorter annual operating time results in less favorable results for the A-USC unit compared to USC. This is the effect of the A USC's higher investment costs. In the lower fuel price and CO_2 charges scenario, the A-USC technology must reduce investment costs.

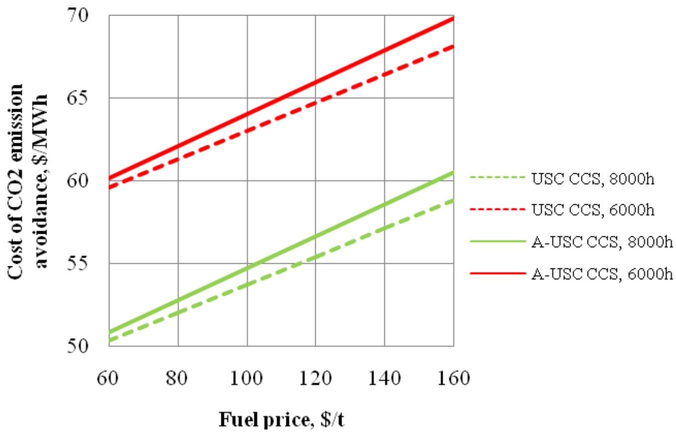

Figure 11: Cost of CO_2 emission avoidance as a function of fuel price for two annual operating time (6,000 and 8,000 h/year)

The costs of avoiding CO_2 emissions are shown in Fig. 11. The cost of emission avoidance is calculated by comparing the cost and emissions of a plant with capture and those of a baseline plant without capture. The cost of the avoided emission is higher for A-USC. It is also about 10 $/MWh higher for a shorter annual operating time (6,000 h). Fig. 12 presents the value of CO_2

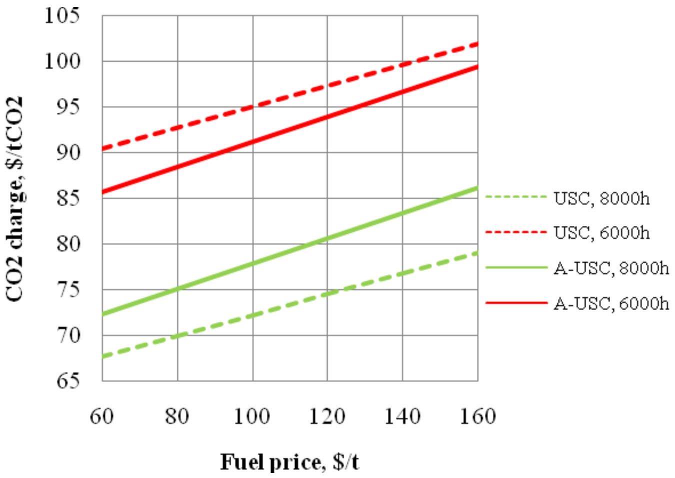

Figure 12: CO_2 charge (value of CO_2 charge above which CO_2 capture becomes economically justified) as a function of fuel price

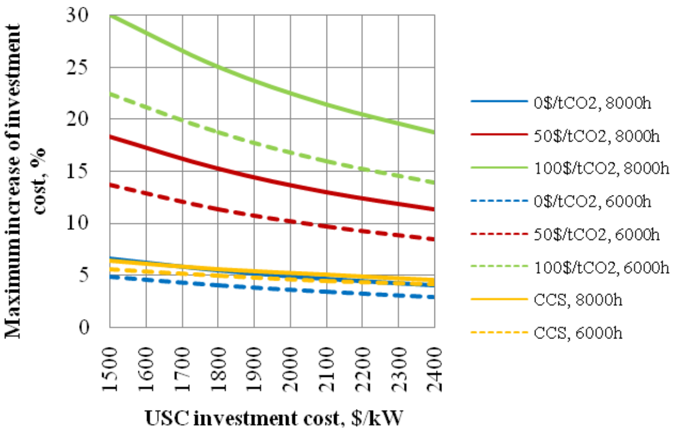

Figure 13: Maximum increase of A-USC power plant investment cost in relation to USC for various CO_2 charges and annual operating time

charges above which the CO_2 capture becomes economically justified. For the A-USC unit with annual operating time of 8,000 h and fuel price of $100/t, the limit is about $78/t$_{CO_2}$, and for USC: $72/t$_{CO_2}$. The higher efficiency of A-USC results in a higher CO_2 charge limit. Fig. 13 presents the maximum increase in A-USC investment cost in terms of the USC investment. For USC investment costs of $1,800/kW, CO_2 charge of $50/t$_{CO_2}$ and annual operating time of 8,000 h, the investment costs for A-USC can be a maximum 15% higher and be economically competitive. The limit of the rise in investment costs is specified with the assumption that the selling price of electricity for USC and A-USC is the same.

One of the most important indices which hardly impacts the efficiency of the power unit integrated with CO_2 capture unit is specific heat duty. It is expected that in the future the heat duty of the CCU will be extremely reduced. Fig. 14 presents the influence of the CCU specific heat

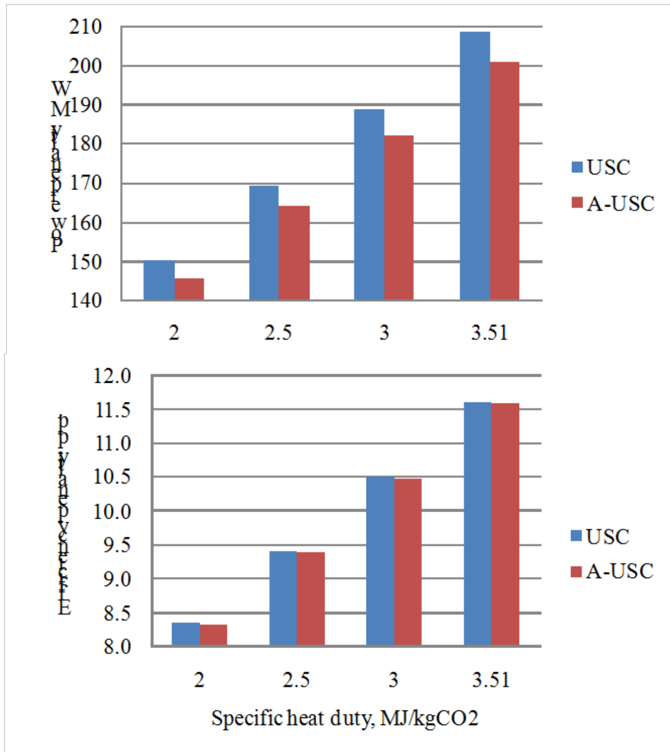

Figure 14: Unit net power and net efficiency for various values of specific heat duty of CO_2 capture unit

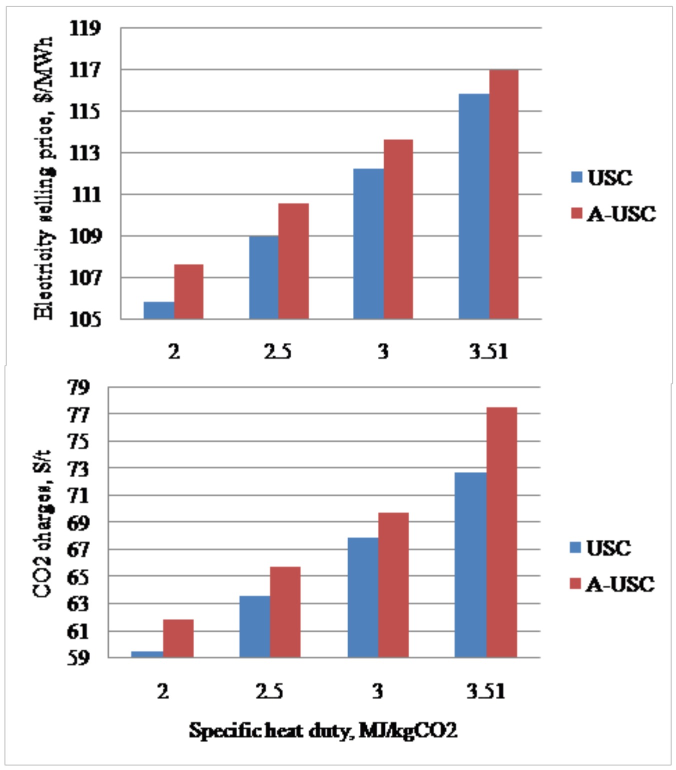

Figure 15: Electricity selling price and CO_2 charges for NPV=0 for various values of specific heat duty of CO_2 capture unit

duty on the unit net power and efficiency. Reduction of the specific heat duty from 3.5 to 2 MJ/kg$_{CO_2}$ can increase the integrated power unit net efficiency by more than 3%. This leads to a reduction of electricity cost. However, the minimum CO_2 charges to provide the economic rationale should be higher than €40 ($55.5). For USC minimum CO_2 charges are $59.5/t and for A-USC: $61.8/t (Fig. 15).

4. Conclusions

The application of advanced ultra-supercritical steam parameters in the future will primarily depend on the success of research and development programs. Very important factors will be the price of construction materials (nickel-based alloys), fuel and the CO_2 charges. A-USC power unit net efficiency is 2.75% higher than USC. The A-USC power unit can achieve favorable economic indicators, especially for the scenario of high fuel price and CO_2 charges. One of the problems facing A-USC technology is the very high investment cost, which relates to the price of nickel-based alloys. It is expected that technological progress will lead to a reduction in the price of nickel-based components. If this price reduction fails to materialize, there will be a question mark next to the implementation of steam parameters at the level of 700°C and higher.

The implementation of CCS technology based on wet chemical absorption MEA is very costly. High CO_2 charges (higher than 55€ for the adopted assumption) could provide a strong economic reason for developing CCS technology.

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Table 1: Time frames of A-USC development programs in different countries

	Start of A-USC development program	Commissioning of A-USC demo plant
Europe	1998	2021
USA	2001	2021
Japan	2008	2020
China	2011	2020
India	2011	2018
South Korea	2012	?

Table 2: Date ranges for technical development of A-USC power plants (Europe, USA) [2]

2012...2020	Commercial SC and USC plants, R&D on A USC
2021...2025	Commercial USC plants, commercial scale A USC demo with CCS
2026...2030	A-USC commercial plant
2031...2050	A-USC with full CCS commercial available

Table 4: Characteristics of USC and A-USC power plant

	USC	A-USC
Live steam	28.5 MPa/600°C	35 MPa/700°C
Reheat steam	5.8 MPa/620°C	7.5 MPa/720°C
Live steam mass flow	649 kg/s	578.4 kg/s
Feed water	303°C	330°C
Condenser	4.5 kPa	4.5 kPa
Cooling water	19.1°C	19.1°C
Fuel	hard coal: LHV=23 MJ/kg,	C=60%, H=3.8%, O=5%, N=1.2%, S=1%, H_2O=9%, ash=20%
Flue gases	CO_2=14.16%, SO_2=0.09%, O_2=3.2%,	N_2=73.78%, H_2O=7.8%, Ar=0.88%
Feed water pump	2×50% electric drive	
Gross power (without CCU)	900MWe	
Net power (without CCU)	841.12 MW_e	838.92 MW_e
Net efficiency (without CCU)	46.29%	49.04%
Specific CO_2 emission	744 $kgCO_2$/MWh	701 $kgCO_2$/MWh
Net power (with CCU)	632.59 MW_e	642.93 MW_e
Net efficiency (with CCU)	34.82%	37.58%