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Life Cycle Assessment of Advanced Zero Emission Combined Cycle Power Plants

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ABSTRACT: This study investigated different concepts for natural-gas-fired power plants with the CO_2 capture, and compared them based on the net plant efficiency and emission of CO_2. The cycles were based on a six oxy-fuel, one post-combustion and two pre-combustion capture concept. This paper presented the results of an environmental evaluation performed by the application of the Life Cycle Analysis (LCA) method using SimaPro model to compare an Advanced Zero Emission Power Plant (AZEP) concept with a conventional combined cycle power plant from 50MW to 400MW. The LCA study was built upon the calculation and the comparison of several impacts (emissions of CO_2, CO, NO_X, and SO_X, consumption of water and primary energy) and several impact categories (climate change, acid rain, ozone depletion and Ecotoxicity). The work was developed entirely using the Eco-indicator99 of the LCA method. The results showed that for all studied impacts, the AZEP power plants have fewer impacts. However, compared to the conventional combined cycle power plants, the total primary energy consumption in the AZEP concept is bigger due to the lower electric efficiency.

Key words: CO_2 capture, zero emissions, combined cycles, LCA, Simapro, Eco-indicator99

INTRODUCTION

The target of the LCA study was the comparison of the environmental burdens associated with different electric power production systems. Some different cases of the same plant size (50 to 400 MW) were considered: the conventional CCGT without CO_2 capture, a CCGT including the AZEP (85,100%) concept (Bolland and Undrum, 2003; Bolland and Saether, 1992; Sundkvist et al., 2001). The LCA study was built upon the calculation and the comparison of several impacts (emissions of CO_2, CO, NO_X, and SO_X, consumption of water and primary energy) and several impact categories (Greenhouse Effect, Acid Rain, Ozone Depletion, and Photochemical Formation). Alternatively, combustion in O_2 / CO_2 atmospheres, whilst enabling almost total CO_2 and NO_X recovery, require expensive and energy-consuming oxygen supplies.A less energy-intensive proposition is based on Mixed Conducting Membranes (MCM), which produce pure oxygen from air. Mixed Conducting Membranes are made from non-porous, metallic oxides that operate at high temperatures of over 700°C, and they have high oxygen flux and selectivity (Möller et al., 2006). These materials consist of complex crystalline structures, which incorporate oxygen ion vacancies. The transport principle for oxygen through the membranes is surface adsorption followed by decomposition into ions, which travel through the membrane by sequentially occupying oxygen ion vacancies. The ion transport is counterbalanced by a flow of electrons in the opposite direction (see Fig. 1). Since this transport process is based on ion diffusion, the selectivity of the membranes is infinite as long as the membrane surface is perfect. The driving force for this oxygen transport is the positive difference in partial pressure between the retentive side and the permeate side of the membrane (Griffin et al.,2005). These scenarios can facilitate assessing the degree of uncertainty of the developed LCA according to the choices made. Outside the limits of this work fall uncertainties due to imprecise knowledge of the different parameters used in the Life Cycle Inventory (LCI), spatial and temporal variability in different parameters of the LCI, and uncertainty due to the inaccuracy of the environmental models used.

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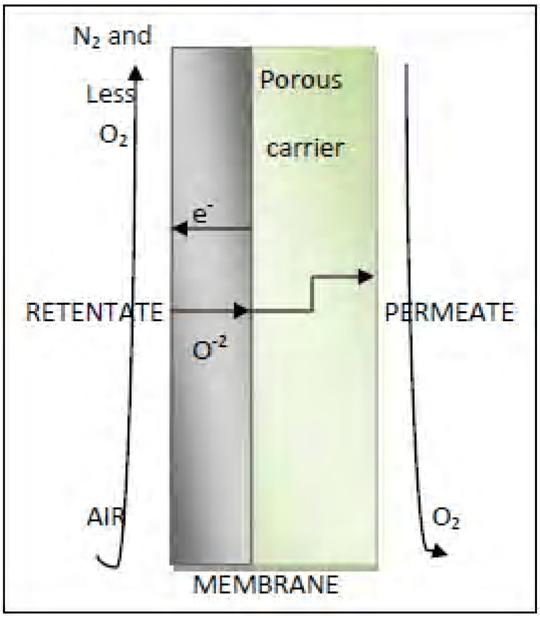

Fig. 1. Mixed Conducting Membrane (Griffin et al., 2003)

MATERIALS & METHODS

Life cycle assessment (LCA) is a method to evaluate the environmental impacts of product systems 'from the cradle to the grave'. The life cycle inventory (LVI) includes emissions and resources used from resource extraction, production, and distribution, to the disposal phase. The impact assessment evaluates the contribution of these emissions and resource uses to specific environmental impacts such as global warming, human toxicity, and biotic resource extraction (Kanokporn and Iamaram, 2011; Veltman et al., 2010). LCA has been developed independently in a number of applications and disciplines, including chemical engineering and energy analysis. The assessment of alternative energy technologies has been one of the most important application areas, and initial assessments have focused on the cumulative (fossil) energy demand, including embodied or "grey" energy. An important motivation in the 1970s was to compare fossil and renewable energy technologies consistently in terms of the energy services they delivered for a given amount of fossil fuel. LCA has since been extended to address a wide range of environmental concerns. It has been standardized by ISO.

In order to facilitate the understanding of the work presented in this paper, the author presents a brief summary of the LCA that serves as the basis for the study: a LCA model of a natural gas combined-cycle power plant with or without CO_2 capture with the objective of identifying the main types of environmental impact throughout the life cycle, in order to deûne possible ways of achieving environmental improvements (Bolland and Undrum, 2003; Bolland and Saether, 1992; Saeedi and Amini, 2007; Salehi et al.,2010; Singh et al., 2011). The ûnal environmental effect after a lifespan of 20 years, and the reduction in emissions and pollution due to the use of a clean energy source was also evaluated. It was analyzed during the different stages of its life cycle, taking into consideration the production of each of its component parts, the transport, the installation, the start-up, and the operation (Clerici,2003). The software used in the environmental analysis was SimaPro7.0 by Pré Consultants (Pre Consultants, 2011). The procedures, details, and results obtained were based on the application of the existing international standards of LCA .In addition, environmental details and indications of materials and energy consumption provided by the various companies related to the production of the component parts were certiûed by the application of the environmental management system ISO14001. According to the requirements of the standard ISO14044, allocation was avoided, since only the production of electrical power was considered as the function of the system in the study. LCA methodology was based on Eco-indicator99. A series of cut-off criteria was established in order to develop the study in practice by deûning the maximum level of detail in the gathering of data for the different components. The main cut-off criterion chosen was the weight of each element in relation to the total weight. This limitation in data collection did not mean a signiûcant weakening of the ûnal results obtained; it simply allowed the researchers to streamline, facilitate, and adjust the LCA study to make it more ûexible. The characterization of each component was obtained from the most important basic data of its manufacture: the raw material required, the direct consumption of energy involved in the manufacturing processes, and the information regarding transport used. This information for speciûc substances included the primary energy consumption use related to the production, transportation, and manufacture of 1 kg of material. Due to limitations of time and cost, the LCA was performed under the following conditions: The cut-off criterion used was the weight of the components. Previous work has indicated that the most efficient and cost-effective utilization of the MCM reactor is its integration into a conventional gas turbine system to produce an Advanced Zero Emissions Power Plant, the AZEP concept (Amini et al., 2008; Ataei et al., 2011; Ataei and Yoo, 2010; Yoo et al., 2010). The combustion chamber in an ordinary gas turbine is here replaced by the MCM-reactor, which includes a combustion chamber, a 'low' temperature heat exchanger, an MCM membrane, and a high temperature heat exchanger

(Bruun,2000). After compression in the ordinary gas turbine compressor, the compressed air at about 18 bar is heated to about 800 - 900°C in the 'low' temperature heat exchanger before it enters the MCM membrane (Ataei et al., 2011). The MCM section combines heat transfer and oxygen transport between the air stream and a sweep gas stream. Permeated oxygen is picked up by means of the circulating sweep gas containing mainly CO_2 and H_2O. The concentration of oxygen in the circulating gas is about 10% at the inlet of the burner. Hot combusted gas then enters the high temperature heat exchanger co-current to the oxygen depleted air stream. This air stream is then heated to 1200°C (up to 1400°C). The pressure difference over the membrane should be kept low (below 0.5 bar) to minimize any leakage. About 10% of the combusted gas is bled off at about 18 bar and heat is recovered by heating a smaller part of the compressed air. The hot oxygen-depleted air is then expanded in the turbine to generate electrical power. Waste heat in both the oxygen-depleted air stream and the CO_2 containing bleed gas stream is recovered in HRSG's by generating steam at various pressure levels and by pre-heating the fuel gas. The steam is utilized in a steam turbine for power generation. The CO_2 containing bleed gas is further cooled to condense water. CO_2 is recovered, compressed from about sweep gas pressure, liquefied, and then pumped to its final pressure (100 bar). The concept allows 100% CO_2 capture, and in this case, has less than 1 ppm v/v NOx in the oxygen-depleted outlet air.

The first system design modeled is a reference system. As such, a traditional CCGT power plant was chosen (see Fig. 2). Data from such plants are in abundance, both in terms of thermo-dynamical performance used as a base in the modeling, and to some extent, cost data. The AZEP 100% case is a "traditional" type of combined-cycle arrangement, but with an MCM-reactor system replacing the traditional combustion chamber (Sundqvist et al., 2001). Air is compressed in the gas turbine and is then heated in the MCM-reactor. Due to MCM material and reactor design limitations, the MCM-reactor outlet temperature was restricted to 1200°C, which is considerably lower than the reference CCGT. A percentage of the oxygen contained in the air, typically 50%, is transferred through the membrane, and is carried along by the CO_2/H_2O sweep gas. The oxygen containing sweep gas then reacts with natural gas to generate heat in a combustion chamber. A share of the sweep gas is bled off to keep the sweep gas mass flow constant in the MCM- reactor. The heat contained in the bleed gas is recovered in a separate CO_2/H_2O HRSG, providing extra steam for the steam cycle and preheating the natural gas fuel. The heat recovery has to be terminated at a higher temperature than in the ordinary HRSG due to the high water content in the bleed gas. After the HRSG, the water is condensed and the remaining CO_2 is compressed and liquefied from the MCM-reactor pressure at around 20 bar to delivery pressure at 100 bar. A layout of the AZEP 100% cycle is shown in Fig. 3. The third alternative, the AZEP 85% case, includes a sequential combustion chamber to increase the turbine inlet temperature. This is to improve the thermal performance of the MCM-based power plant (Asen et al.,2003; Griffin et al., 2005; Möller; 2006). Fig. 4 shows a power plant including a sequential burner increasing the turbine inlet temperature (TIT) to 1327ºC on the airside using natural gas as fuel. Table 1 lists the power plant construction material requirements used in this study. These values were based on a study that examined power generation via a number of technologies - for example, a 400 MW NGCC system.

Table 2 is a comparison between the AZEP power-plant concept (oxy-fuel) and the standard CCGT without CO_2 capture from 50MW up to 400MW.
Net plant efficiency is defined as:

$$\eta_{cycl} = \frac{\left(\sum \dot{W}_{exp} - \sum \dot{W}_{c}\right)\eta_{t\to e} - \dot{W}_{Fc} - \dot{W}_{AD/Ac} - \sum \dot{W}_{consumer}}{m_{F\,LHV}} \quad (1)$$

The first term is related to thermodynamic work of gas turbines, steam turbines, and gas turbine compressors. This net thermodynamic work is multiplied by a turbine to electricity grid efficiency, $\eta_{t\to e}$, which for most of the concepts is 0.97. The 2nd term is the fuel cell electric work, while the 3rd term concerns the losses related to DC to AC conversion. The last term is the sum of work related to consumers as auxiliaries, pumps, ejectors, CO_2 compression, O_2 production and compression, amine absorption, and utilities. The base case of this LCA used the typical natural gas pipeline composition listed in the Chemical Economics Handbook (Lacson, 1999), which was adjusted to include H_2S (4 ppmv; based on the specifications above). The composition of the natural gas transported to the power plant is shown in Table 3. To show the diversification of natural gas compositions found throughout the world, the range of wellhead component values is also listed in Table 3.

RESULTS & DISCUSSION

The LCA study, built upon the calculation and the comparison of several impacts (emissions of CO_2, CH_4, CO, NO_X, and SOx, consumption of water and primary energy) and several impact categories (Greenhouse Effect or Global Warming Potential, Acid Rain, Ozone Depletion, and Photochemical Formation), shows a very good environmental rank for the systems based on the AZEP concept, as seen in Table 4 and in Fig. 5. This is

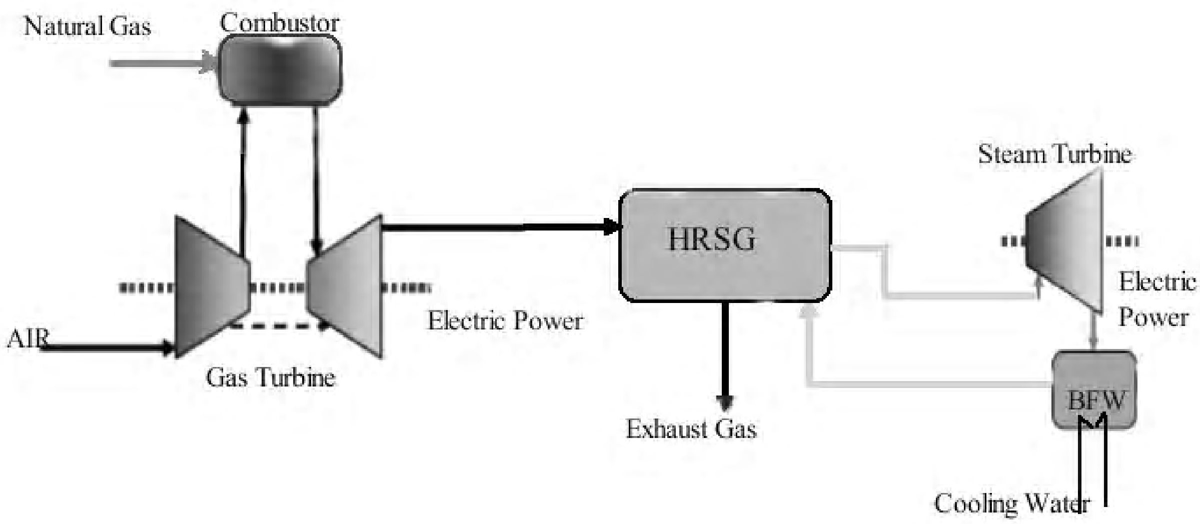

Fig. 2. The reference CCGT cycle (Möller et al., 2006)

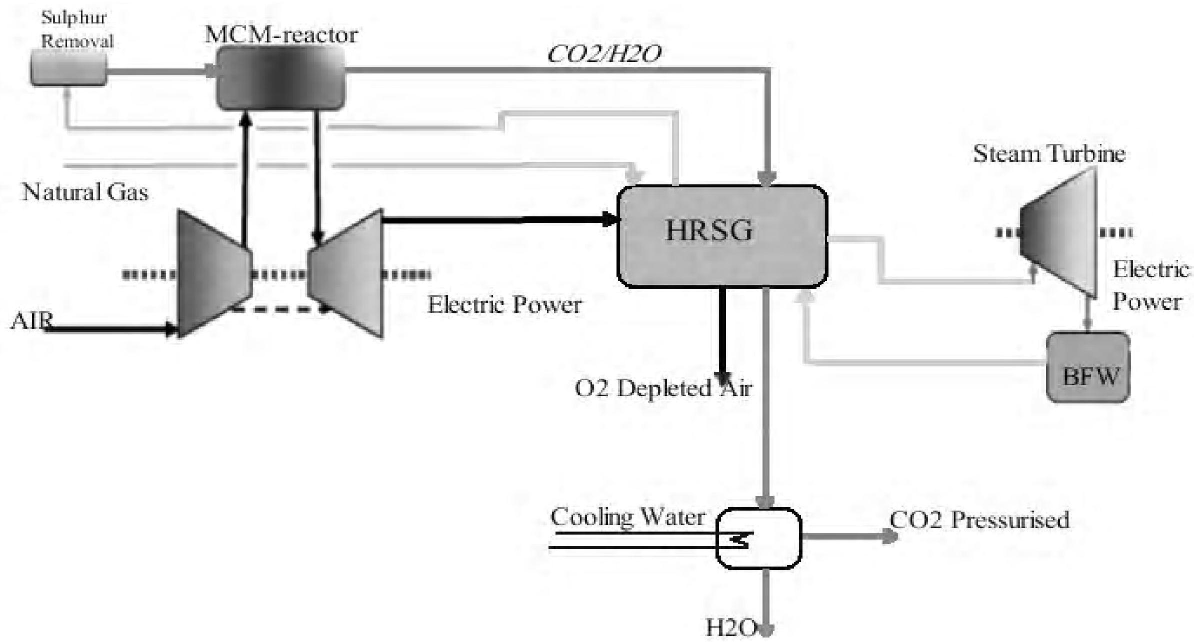

Fig. 3. The AZEP 100% case (Möller et al., 2006)

Table 1. Power plant materials requirement for 400MW

Components		Amount
Constructional		
	Aluminum (kg)	440000
	Concrete (m3)	6000
	Copper (kg)	440000
	Rock wool(kg)	660000
	Polyethylene (kg)	1300000
	Chromium steel (kg)	1800000
	Reinforcing steel(kg)	8800000
	Nickel, 99.5%(kg)	6300
	Chromium (kg)	976
	Cobalt (kg)	720
	Ceramic tiles(kg)	4200
Operational		
	Natural gas(Mj)	154000000

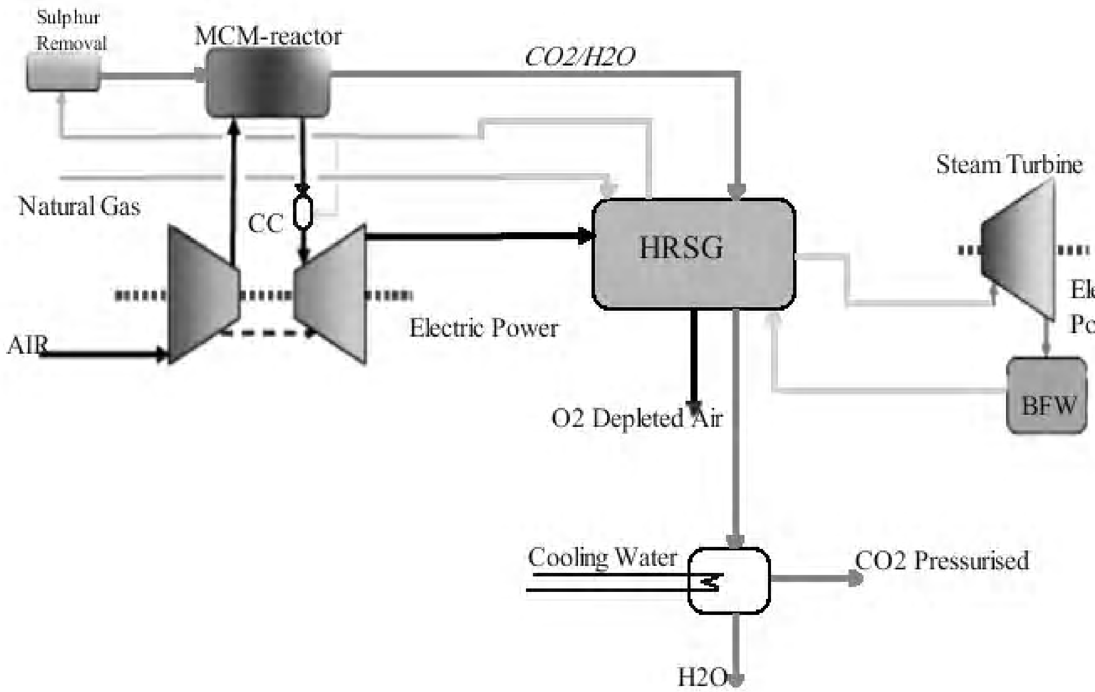

Fig. 4. The AZEP 85% case. (Möller et al., 2006)

Table 2. Process Simulation Results of the 50 MW to 400 MW Power Plant Cases

Plant Data		Net power output (MW)	Plant fired heat (MJ/s)	Net plant efficiency (LHV) (%)	CO2 compression power (MW)
50 MW(15-50)	CCGT	63.9	120.6	53	-
	AZEP 100%	46.2	95.4	48.5	0.49
	AZEP 85%	53.9	107.1	50.3	0.47
100MW(51-100)	CCGT	112	200.2	54.7	-
	AZEP 100%	87	149.5	48.9	0.78
	AZEP 85%	98	182	51.5	0.7
200MW(101-200)	CCGT	208	339.1	56	-
	AZEP 100%	143	290	49.2	1.67
	AZEP 85%	178	314.7	52	1.51
400MW(201&uppe)	CCGT	400	692.4	57.9	-
	AZEP 100%	248.1	500.5	49.6	2.95
	AZEP 85%	300.4	562.5	53.4	2.85

Table 3. Natural Gas Composition

Component	Pipeline composition	Typical range of wellhead	Typical range of wellhead
	Mol % (dry)	Low value	High value
Carbon dioxide (CO2)	0.5	0	10
Nitrogen (N2)	1.1	0	15
Methane (CH4)	94.4	75	99
Ethane (C2H6)	3.1	1	15
Propane (C3H8)	0.5	1	10
Iso-butane (C4H10)	0.1	0	1
N-butane (C4H10)	0.1	0	2
Pentanes + (C5+)	0.2	0	1
Hydrogen sulfide (H2S)	0.0004	0	30
Helium (He)	0	0	5
Heat of combustion, LHV	48,252 J/g (20,745Btu/lb)	-	-
Heat of combustion, HHV	53,463 J/g (22,985Btu/lb)	-	-

(a) Taken from Chemical Economics Handbook (Lacson, 1999) and adjusted to include H2S.

(b) Taken from Ullmann's Encyclopedia of Industrial Chemistry, 1986

particularly evident for two global effects, the Greenhouse Effect and the Acid Rain Potential, and for two impacts, the CO_2, and NO_X emissions. For all the studied impacts and impact categories, the AZEP power plants have less environmental impacts. However, due to lower electric efficiencies, the total consumption of primary energy is larger for both the CO_2-capturing concepts compared to the conventional CCGT plants. The impact category Global Warming Potential (expressed in CO_2 equivalents) is dominated by Combustion Emissions. Of the other emission sources (Gas Life Cycle, Auxiliary Systems, Liquid Waste), only the Gas Life Cycle emissions have a non-negligible impact on the Global Warming Potential. In the LCA study, the emissions of CO and CH_4 (per kWe (LHV) of fuel) for the AZEP plants were assumed to be on the same level as in conventional CCGT plants. In the AZEP process, however, these components are mainly flashed off after the CO_2 liquefaction stage together with some nitrogen and oxygen. Probably more than 90% of these carbon components can be burnt in a catalytic converter and recycled to the CO_2 compression train Appel at el, 2002; Carroni et al., 2003; Carroni et al., 2002; Eriksson et al., 2006; Mantzaras et al., 2006; Mantzaras et al., 2000; Mark et al., 1996). Thus, the 'Potential of Formation of Oxidants Agents by Photochemical Effect' would be reduced accordingly. AZEP with no sequential burner will produce very little NOx since there is no combustion in the air stream. In the case of sequential combustion in the air stream before the expander, some NOx might be formed, dependent on the combustion temperature. This has not yet been studied. However, the NOx formation will be significantly lower than in a conventional CCGT. Electricity generation from the NGCC power plant without CO_2 capture implies an emission of 425 g_{CO2}/kWh, with over 86% direct emission from fuel combustion. In the case of the NGCC power plant coupled with carbon capture and a storage system, this emission intensity decreases to 125 g_{CO2}/kWh. Fig. 5 illustrates the CO_2 account and compares the emission sources for both the cases, with and without CCS. The capture process at the power plant facility captures 90% of the CO_2 from the flue gas. However, additional CO_2 is generated from fuel combustion because of the energy penalty, operational inputs, and the infrastructure required for capture, operation, transport, and storage. The increased CO_2 production results in a larger amount of 'CO_2 generated per unit of product' (508 g_{CO2}/kWh).

Total CO_2 captured in the production of electricity with the CCS system is about 383g_{CO2}/kWh, reducing the CO_2 capture efficiency over the complete life cycle to 75%. In addition to CO_2 emissions, there are various other direct and indirect emissions throughout all the processes, from raw material extraction for fuel, infrastructure, and other required materials to waste treatment and disposal. Fig. 6 compares the absolute scores after characterization for 'with CCS' and 'without CCS' systems. The results show that there is an increase in all environmental impacts. These scores reveal the magnitude of the impact emanating from the whole life cycle of electricity generation. The impacts are unevenly distributed over various processes (natural gas combustion at the power plant, CO_2 capture, infrastructure, solvent production) and locations (offshore natural gas production facilities, chemical

Table 4. Comparing 1 p 'Life cycle AZEP100%', 1 p 'Life cycle AZEP85%' and 1 p 'Life cycle NGCC' Method: Greenhouse Gas Protocol V1.00 / C02 eq (kg) Indicator: Characterization (400MW)

Impact category	Unit	Life cycle AZEP100%	Life cycle AZEP85%	Life cycle NGCC
Fossil CO2 eq	kg CO2eq	30660571	32482622	41056289
Biogenic CO2 eq	kg CO2eq	307221.75	307675.84	309914.55
CO2 eq from land transformation	kg CO2eq	454.98486	459.20713	479.14303
CO2 uptake	kg CO2eq	370831.3	371274.13	373455.04

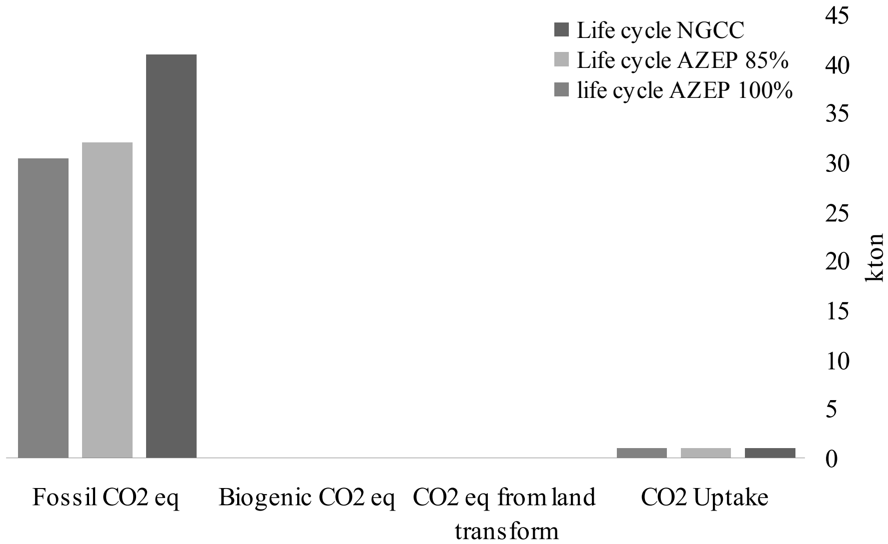

Fig. 5. Comparing 1 p 'Life cycle AZEP100%', 1 p 'Life cycle AZEP85%', and 1 p 'Life cycle NGCC'Method: Greenhouse Gas Protocol V1.00 / C02 eq (kg) Indicator: Weighting

manufacturing sites, power plant facilities, iron and steel industries, mining sites, etc.). The Damage assessment for LCI (AZEP 100%) is shown in Fig. 7. Direct emissions at the power plant facility consist of various substances, such as NO_X, SO_X, acetaldehyde, formaldehyde, and hazardous reclaimed wastes (Veltman *et al.,* 2010). The capture process, while capturing CO_2, reduces NO_x, SO_2, and particulate emission. However, their net removal efficiency per kWh electricity generation is lower than the designed performance parameter, due to the increased combustion of natural gas to meet the energy requirements of the capture process. The results of single score LCI analyzing for NGCC and AZEPs are shown in Figs 8,9,10.

The energy penalty also results in increased emissions of CH_4, CO, and other pollutants that are not captured by the process. These compounds have potential for causing various environmental impacts. Table 6 compares impacts due to direct emissions from the facility and their contributions to the total impact, quantifying the immediate hazards from capture technology. The contribution analysis in Table 6 shows that the direct emissions at plant facilities are responsible for 45% and 57% of the total acidification and marine eutrophication, respectively for 85% of NGCC and 100% of AZEP concepts, respectively. The capture process reduces the score due to SO_2 and NO_2 removal; however, the reduction is insignificant to the impact from increased emissions of NOx. Direct emissions from the plant facility constitute 45% of the total life cycle score. NO_x emission from fuel combustion is the main contributor to this impact (94% of the direct impact). The second major source (40%) of the impact is due to emissions of CH_4 and SO_2 in the natural gas production chain and about 14% of the impact is from infrastructure demands. The results of LCI analysis with weighting indicator for NGCC and AZEPs are shown in Tables 7,8,9.

Particulate matter formation potential (PMFP) results show an increase of 33% in the total life cycle score. 37% of the total PMFP impact is attributed to direct emissions from the plant facility with NO_x emissions from fuel combustion being the largest contributor (93%). Natural gas production constitutes 32% of the impact and 31% is from infrastructure demands.

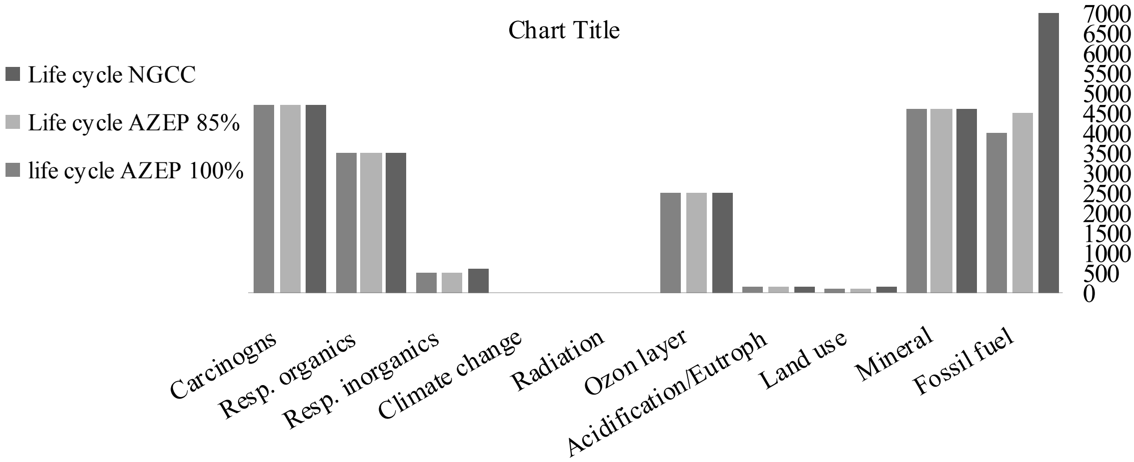

Fig. 6. comparing 1 p 'Life cycle AZEP100%', 1 p 'Life cycle AZEP85%' and 1 p 'Life cycle NGCC' Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A /Normalization

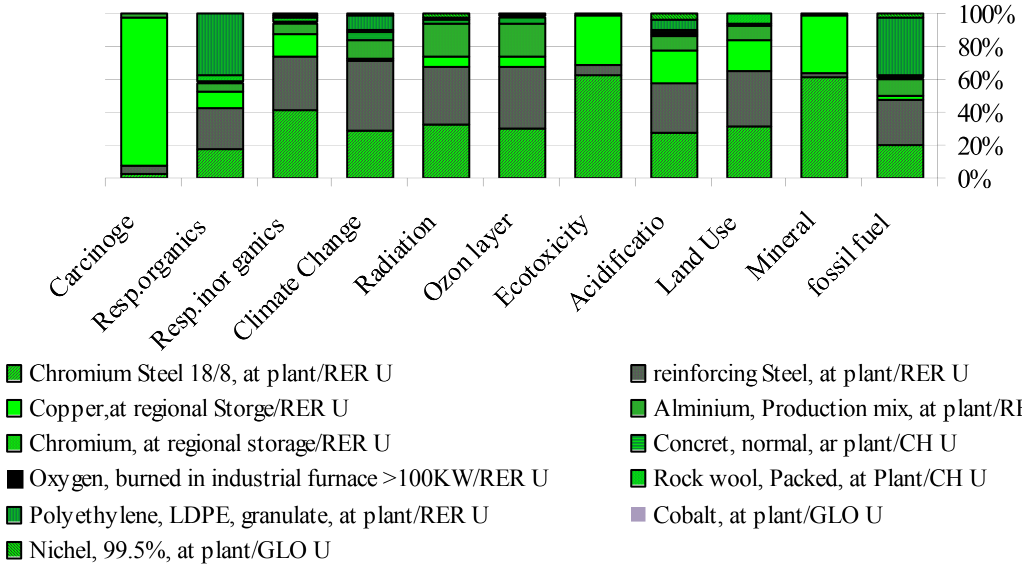

Fig.7. Analysing 1 p 'AZEP100 % (400MW) Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A/Damage assessment

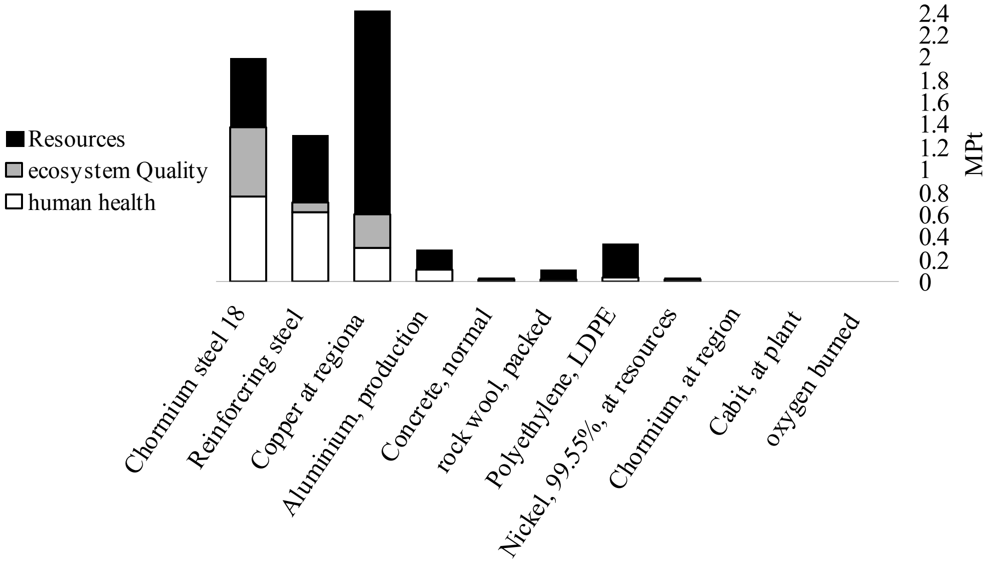

Fig. 8. Analysing 1 p 'AZEP100 % (400MW) Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A/Single score

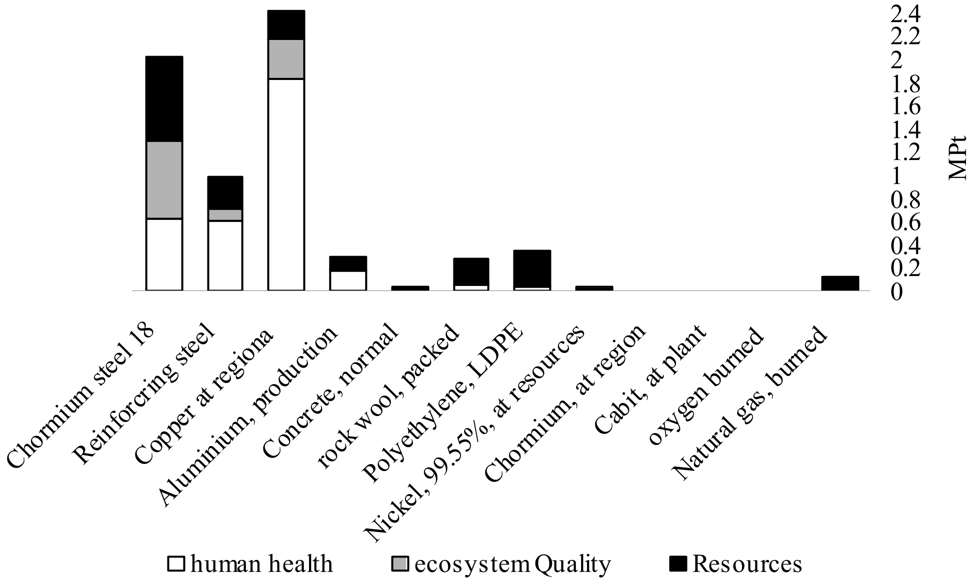

Fig. 9. Analysing 1 p 'AZEP85 % (400MW) Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A /Single score

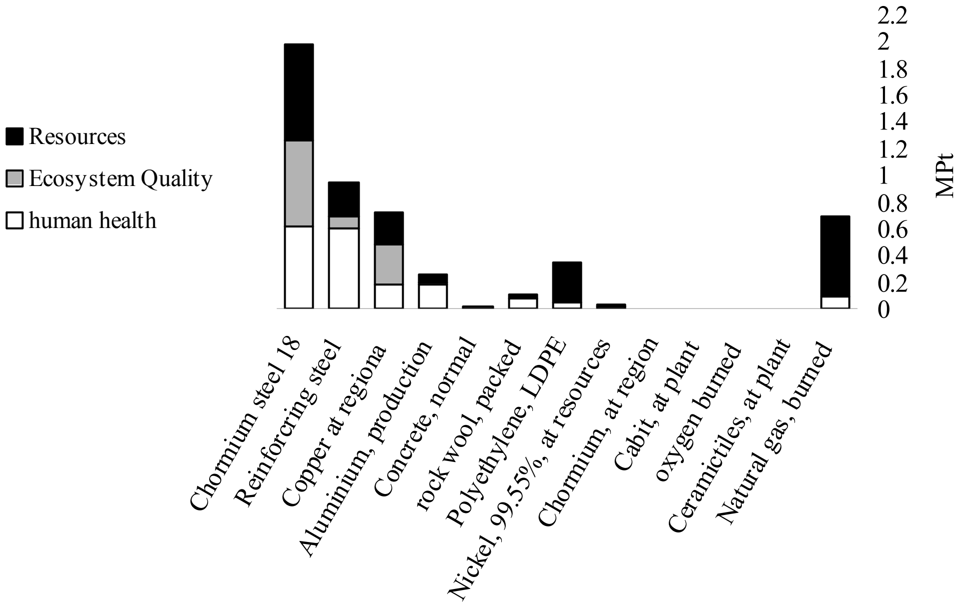

Fig .10. Analysing 1 p 'NGCC (400MW) Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A /Single score

Table 6. Comparing 1 p 'Life cycle AZEP100%', 1 p 'Life cycle AZEP85%', and 1 p 'Life cycle NGCC'Method: Selected LCI results V1. Indicator: Characterization (400MW)

Impact category	Unit	Life cycle AZEP100%	Life cycle AZEP85%	Life cycle NGCC
NMVOC	kg	21853.981	22566.673	25920.419
Carbon dioxide fossil	kg	27636454	29348681	37405562
Sulphur dioxide	kg	129772.91	130391.17	133306.27
Nitrogen oxides	kg	71098.875	72204.554	77410.575
Particulates, <2.5 µm	kg	32127.573	32151.153	32299.169
Land occupation	m2	1134838.7	1135914.5	1141244.4
BOD	kg	42844.845	42961.601	43514.316
Cadmium	kg	0.003472432	0.00347964	0.003514453

Table7. Analyzing 1 p 'AZEP100 % (400MW)' Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A Indicator: Weighting

Impact category	Unit	Total	Chromium steel 18/8, at plant/RER U	Reinforcing steel, at plant/RER U	Copper, at regional storage/RER U	Aluminium, production mix, at plant/RER U	Concrete, normal, at plant/CH U	Rock wool, packed, at plant/CH U	Polyeth-ylene, LDPE, granulate, at plant/RER U	Nickel, 99.5%, at plant/GLO U	Chromium, at regional storage/RER U	Cobalt, at plant/GLO U	Oxygen, burned in industrial furnace > 100kW/RER U
Total	Pt	6236489.7	2040706.2	964955.9	2439223	270740.31	40816.852	94719.804	333833.33	42853.526	2001.5883	729.56932	5909.5788
Carcinogens	Pt	1879978.7	72801.775	107032.77	1626241.1	48568.484	2381.8281	4992.3808	1117.9759	15289.097	188.43539	64.523066	1300.326
Resp. organics	Pt	730.79275	132.45541	247.28525	54.492384	34.623216	13.47189	27.147816	217.50201	2.5211893	0.24415407	0.34720413	0.70222054
Resp. inorganics	Pt	1373149.3	518850.51	443592.23	212494.31	80833.685	11932.072	57818.173	28675.236	16518.593	489.53026	378.57519	1566.3643
Climate change	Pt	167694.97	44200.291	70461.606	4542.3698	20298.024	8553.2905	4040.7903	14474.148	373.66579	141.26057	32.692088	576.82696
Radiation	Pt	2938.795	913.54636	1109.586	128.72835	528.69299	95.985025	101.06916	0.93725111	8.9906109	5.7333798	1.1126701	44.413115
Ozone layer	Pt	34.640037	10.609169	13.507224	1.6873655	6.1358679	1.4317327	0.91149182	0.024767956	0.14151481	0.049629925	0.01164694	0.12962665
Ecotoxicity	Pt	996460.69	636275.12	62716.493	280176.42	11120.576	808.87539	1246.2596	266.6429	3112.5786	324.19364	14.592082	398.9449
Acidification/ Eutrophication	Pt	45807.401	11509.052	14275.984	9480.2287	3808.5699	1390.9084	1485.4709	2735.876	950.47608	24.4443	36.607091	109.78308
Land use	Pt	32210.408	10165.206	10990.805	5198.7091	2492.531	611.47116	2496.2713	12.420231	136.41811	16.917469	39.586898	50.070869
Minerals	Pt	936001.77	582943.86	46301.517	277794.92	22479.178	424.38699	1306.8969	4.2938776	4550.269	71.050657	9.3512702	116.03324
Fossil fuels	Pt	801482.22	162903.77	208214.12	23110.039	80569.808	14603.131	21204.433	286328.27	1910.7743	739.7288	152.17012	1745.9845

Table 8. Analyzing 1 p 'AZEP85 % (400MW)' Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A Indicator: Weighting

Impact category	Unit	Total	Chromium steel 18/8, at plant/RER U	Reinforcing steel, at plant/RER U	Copper, at regional storage/RER	Aluminium, production mix, at plant/RER U	Concrete, normal, at plant/CH U	Rock wool, packed, at plant/CH U	Polyethylene, LDPE, granulate, at plant/RER U	Nickel, 99.5%, at plant/GLO U	Chromium, at regional storage/RER U	Cobalt, at plant/GLO U	Oxygen, burned in industrial furnace >100kW/RER U	Natural gas, burned in industrial furnace >100kW/RER U
Total	Pt	6353506.2	2040706.2	964955.9	2439223	270740.31	40816.852	94719.804	333833.33	42853.526	2001.5883	729.56932	4873.4838	118052.64
Carcinogens	Pt	1880123.3	72801.775	107032.77	1626241.1	48568.484	2381.8281	4992.3807	1117.9759	15289.097	188.43539	64.523066	1072.3467	372.52923
Resp. organics	Pt	750.21094	132.45541	247.28525	54.492384	34.623216	13.47189	27.147816	217.50201	2.5211893	0.2441540	0.3472041	0.5791039	19.5413
Resp. inorganics	Pt	1377148.1	518850.51	443592.23	212494.31	80833.685	11932.072	57818.173	28675.236	16518.593	489.53026	378.57519	1291.742	4273.4662
Climate change	Pt	177568.38	44200.291	70461.606	4542.3698	20298.024	8553.2905	4040.7903	14474.148	373.66579	141.26057	32.692088	475.69496	9974.5496
Radiation	Pt	2941.1515	913.54636	1109.586	128.72835	528.69299	95.985025	101.06916	0.9372510	8.9906109	5.7333798	1.1126701	36.6264	10.143263
Ozone layer	Pt	40.780478	10.609169	13.507224	1.6873655	6.1358679	1.4317327	0.9114918	0.0247679	0.1415148	0.0496299	0.0116469	0.1068999	6.1631685
Ecotoxicity	Pt	996547.73	636275.12	62716.493	280176.42	11120.576	808.87539	1246.2596	266.64289	3112.5786	324.19364	14.592082	329.00002	156.98048
Acidification/ Eutrophication	Pt	46351.119	11509.052	14275.984	94802287	3808.5699	1390.9084	1485.4709	2735.876	950.47608	24.4443	36.607091	90.535394	562.96577
Land use	Pt	32622.714	10165.206	10990.806	5198.709	2492.5354	611.47105	2496.2714	12.420006	136.41811	16.917472	39.586898	41.292211	421.08037
Minerals	Pt	936037.87	582943.86	46301.517	277794.92	22479.178	424.38699	1306.8969	4.2938668	4550.269	71.050657	9.3512702	95.689752	56.4457
Fossil fuels	Pt	903374.89	162903.77	208214.12	23110.039	80569.808	14603.131	21204.433	286328.27	1910.7743	739.7288	152.17012	1439.8703	102198.78

Table 9. Analyzing 1 p 'NGCC (400MW)' Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A Indicator: Weighting

Impact category	Unit	Total	Chromium steel 18/8, at plant/RER U	Reinforcing steel, at plant/RER U	Copper, at regional storage/RER U	Aluminium, production mix, at plant/RER U	Concrete, normal, at plant/CH U	Rock wod, packed, at plant/CH U	Polyethylene, LDPE, granulate, at plant/RER U	Nickel, 99.5%, at plant/GLO U	Chromium, at regional storage/RER U	Cobalt, at plant/GLO U	Natural gas, burned in industrial furnace >100kW/RER U
Total	Pt	6904862.8	2040706.2	964955.82	2439223	270740.32	40816.852	94719.806	333833.33	42853.526	2001.5883	729.56932	673337.3
Carcinogens	Pt	1880849.7	72801.773	107032.76	1626241.1	48568.486	2381.8281	4992.3809	1117.9759	15289.097	188.4354	64.523066	2124.7963
Resp. organics	Pt	841.59128	132.45541	247.28524	54.492384	34.623219	13.47189	27.147816	217.50201	2.5211893	0.24415408	0.34720413	111.45779
Resp. inorganics	Pt	1396666.1	518850.5	443592.2	212494.31	80833.69	11932.072	57818.174	28675.236	16518.593	489.53027	378.57519	24374.585
Climate change	Pt	224027.82	44200.291	70461.604	4542.3698	20298.025	8553.2905	4040.7904	14474.148	373.66579	141.26057	32.692088	56891.876
Radiation	Pt	2952.7052	913.54635	1109.586	128.72835	528.693	95.985025	101.06917	0.93725086	8.9906109	5.7333799	1.1126701	57.854164
Ozone layer	Pt	69.672863	10.609168	13.507222	1.6873655	6.1358681	1.4317327	0.91149184	0.024767955	0.14151481	0.049629926	0.01164694	35.152887
Ecotoxicity	Pt	996972.11	636275.12	62716.484	280176.42	11120.578	808.87534	1246.2598	266.64293	3112.5786	324.19364	14.592082	895.3701
Acidification/ Eutrophication	Pt	48912.003	11509.052	14275.982	9480.2287	3808.5702	1390.9084	1485.471	2735.876	950.47608	24.444301	36.607091	3210.9899
Land use	Pt	34570.348	10165.207	10990.805	5198.7089	2492.5324	611.47109	2496.2719	12.420114	136.41811	16.917484	39.586898	2401.7177
Minerals	Pt	936214.83	582943.86	46301.508	277794.92	22479.18	424.38694	1306.897	4.293905	4550.269	71.05066	9.3512702	321.94952
Fossil fuels	Pt	1382786	162903.76	208214.1	23110.039	80569.811	14603.131	21204.433	286328.27	1910.7743	739.72881	152.17012	582911.56

CONCLUSION

The different uncertainties arising from the options given during the development of the LCA of a combined cycle power plant (or AZEP) have been analyzed in this study, using the Eco-indicator99 LCA method. In addition, the impact that these scenarios may present on the ûnal LCA has also been assessed. Undoubtedly, the choices made at the turbine maintenance stage have an important effect on the results of the LCA. Therefore, it is necessary to precisely analyze the average of major corrections that a model of combined cycle power plant (or AZEP) may experience along its 20 years of life. Another issue that signiûcantly inûuences the ûnal results of the LCA study of an AZEP is the considerations made about recycling and reuse of components and materials from an environmental point of view. Compared with a conventional CCGT the optimized AZEP concept for the 50 MW size gives 4.5 percentage points reduction in thermal efficiency (LHV) with 100% CO_2 capture including pressurization of CO_2 to 100 bar. In the AZEP 50 MW case with a CO_2 capture of 85% the penalty in thermal efficiency is less than 3.0 percentage points compared to a standard CCGT. The 400 MW size has more penalty for the 100% CO_2 capture case and therefore needs a sequential combustion before the expander to improve the thermal efficiency. In an AZEP 400 MW case with 85% CO_2 capture the penalty in thermal efficiency (LHV) is 4.5 percentage points. The LCA study shows a very good environmental rank for the systems based on the AZEP concept. This is particularly evident for two global effects, the Greenhouse Effect (Global Warming Potential) and the Acid Rain Potential, and for two impacts, the CO_2 and NO_x emissions. For all studied impacts and impact categories, the AZEP power plants have fewer impacts. However, compared to the conventional CCGT plants the total consumption of primary energy is bigger for both the CO_2 capturing concepts due to lower electric efficiencies for these concepts.

Abbreviation

AZEP Advanced Zero Emissions Plant
LCA Life Cycle Assessment
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
BFW Boiler Feed Water System
CCGT Combined Cycle Gas Turbine
HP High Pressure
LP Low Pressure
HRSG Heat Recovery Steam Generator
MCM Mixed Conducting Membrane
TIT Turbine Inlet Temperature
HTP Human Toxicity Potential
PMFP Particulate Matter Formation Potential
BOD Biological Oxygen Demand
NMVOC Non-Methane Volatile Organic Compounds
W_{FC} Fuel cell electrical work
W_{exp}, W_C Thermodynamic work of gas turbines, steam turbines, and gas turbine compressors
$W_{AD/AC}$ Losses related to DC to AC conversion
$W_{consumers}$ Work related to auxiliaries, pumps, ejectors, CO_2 compression, O_2 production and compression.
$\acute{\eta}_{t\rightarrow e}$ Electricity grid efficiency

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