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CARBON FOOTPRINT COMPARATIVE ANALYSIS FOR EXISTING AND PROMISING THERMAL POWER PLANTS

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The power production industry is the main greenhouse gas emitter that makes its contribution to global warming. The greenhouse gas emission takes place in fuel production, transportation, and combustion. A prospective method for emission mitigation is the transition to organic fuel-burning facilities with small emissions by capturing carbon dioxide. Power consumption on the carbon dioxide capture remarkably reduces the efficiency of these facilities, which leads to increasing of fuel consumption and greenhouse gas emission because of the larger fuel production and transportation. Based on the material balance method, taking into account system effect of changes in efficiency and amount of fuel consumed, the paper estimated the carbon footprint over a twenty-year lifecycle for following thermal power plants types: combined cycle and oxy-fuel combustion plants for both natural gas and coal with internal gasification. It is shown that the transition to oxygen-fuel plants can reduce the carbon footprint near 90% for natural gas and near 75% for coal. The study also demonstrates the positive effect of carbon capture and storage system implementation for reducing carbon footprint near 75% for natural gas and near 70% for coal.

Keywords: carbon footprint, thermal power plant, combined cycle facility, oxy-fuel cycle, organic fuel, coal gasification

Introduction

ESG (Environmental, Social, Corporate Governance) [1] is a business direction that provides the business social devotion combined with company contribution into the social development and environmental improvement. Since 2015 the world economy shows a distinct trend to the ESG management supported by the ESG investment of up to 30% [2]. The ESG investments since 2014 show a positive influence upon the investment portfolio profitability. The companies that changed to the ESG management may expect larger investments [2]. The main vector of the ESG management introduction for fuel and energy companies is the transition to environment harmless technology and the reduction of harmful emissions and first of all of greenhouse gas emissions [3]. The main greenhouse gases produced in the power production by fossil fuel combustion are the hydrocarbon combustion products, carbon dioxide [3], nitrogen monoxide, and methane as the under-burning product. In power distribution, the main greenhouse gas is the sulfur hexafluoride [4] that is used as an isolating fluid in transformers and high voltage switches. The total greenhouse influence upon the climate changes is assessed by the carbon footprint that is the total greenhouse emission including its global warming potential (GWP) [5] measured in the CO_2 equivalent tons (CO_{2e}).

Some states especially in the EU already have legal movers for the greenhouse emission mitigation that are introduced in the form of carbon dioxide emission quotas that are a subject of stock trade [6, 7]. By the 2022 beginning, these quotas mean the price is above 100 euro for CO_2 ton. Moreover, the EU states introduce a trans-border carbon tax for the products with high carbon footprint including electricity production, the tax will be in power since 2023. So nowadays for the fuel-energy complex, it is topical to reduce the carbon footprint of their products by the transition to renewable power sources and modernization of the existing traditional facilities. A reliable assessment of the new technology practicability requires an accurate analysis of the carbon dioxide footprint effect including the product life evaluation.

The carbon footprint analysis has to correspond to the international standard «ISO 14067:2018 Greenhouse gases. The carbon footprint of products. Requirements and guidelines for quantification». This standard fixes topics and requirements to the carbon footprint analysis, cadaster order, and reports on the product carbon footprint including the life cycle assessment according to the International Standards for the product life cycle analysis ISO 14040 and ISO 14044.

The ISO 14067:2018 standard makes a base for a few methods for the carbon footprint analysis and the issue of reports and cadaster on the greenhouse gas emission as the following:

- EIB Project Carbon Footprint Methodologies [8],
- IPCC manual for the carbon footprint analysis [9],
- PAS 2050 [10],
- GHG Protocol Product Standard [11].

PAS 2050 and GHG Protocol Product Standard are the only methods that involve the record regulations of all stages of product life. These methods are based on similar principles but have some minor distinctions, not leading to difference in calculation of total carbon footprint more than 5%. GHG Protocol Product Standard is the most usual method used by 90% of the S&P Fortune 500 companies, so this method is the main manual in this investigation.

Among the existing thermal power plant (TPP) types, the most environmentally friendly with the smallest greenhouse emission are the natural gas combines cycle plants (NGCC). These facilities have high efficiency above 60% and the resulting lower fuel consumption than Steam Turbine (ST) and Gas Turbine (GT) facilities [12]. The combined cycle power plant's main fuels are natural gas (in NGCC) or coal with the internal gasification cycle (in IGCC). In the internal gasification combined cycle coal is transformed into the syngas that is supplied to a combustor. This technology is a cleaner coal technology because it does not produce the fine-dispersed dust that is the most harmful product of direct coal combustion.

The Carbon Capture and Storage (CCS) systems are prospective technologies for the mitigation of carbon dioxide emissions. The CCS introduction promises an 89% reduction in CO_2 emission. The accumulated carbon dioxide in the future may be used for an increase in oil production rate in EOR-CO2 technology [13, 14]. An important CCS feature is the possibility to apply this technology both for the newly constructed TPP and the modernization of the existing ones. The CCS shortage is a remarkable TPP net efficiency due to the larger internal power consumption. This may reduce the CO_2 mitigation effect by the larger emission in fuel mining and transportation. The nitrogen oxides NOx has no greenhouse effect but their emission is the most environmentally harmful with a negative influence upon the health of people, animals, and plants. The most effective NOx mitigation technology is a selective catalytic recovery (SCR) [15]. The SCR technology recovers NO_x to N2 and water by the ammonia injection, its maximal efficiency may be 95%, and the net efficiency drop is minor and is below 0.5%

The prospective oxygen-fuel power facilities based on the Allam cycle [16, 17] are the nearest to carbon neutrality. In the Allam cycle facilities, natural gas burns in pure oxygen. The produced by combustion carbon dioxide operates as a working fluid, and then is dried and captured. The Allam cycle is closed which provides small carbon dioxide emissions. Now the carbon dioxide emissions of Allam cycle facilities [18, 19] are evaluated as 1% of the total amount of CO2 produced by combustion. This emission is mostly caused by leakages first of all from the facility rotating parts, compressors, and turbines. The oxygen-fuel facility shortage is its smaller net efficiency than the NGCC one due to the additional power consumption in air split and CCS blocks.

This paper compares existing and prospective gas and coal firing TPP. The facilities are compared on the total carbon footprint in all stages of the power production operation:

- NGCC and IGCC facilities to evaluate the existing TPP carbon footprint,
- NGCC and IGCC with CCS and the NOx mitigation system to evaluate the CCS technology efficiency and the prospects for existing TPP modernization,
- Oxygen-fuel Allam cycle facility to evaluate the prospective low emission TPP carbon footprint.

1. Fuel combustion and CO_2 generation in thermal and electrical power generation

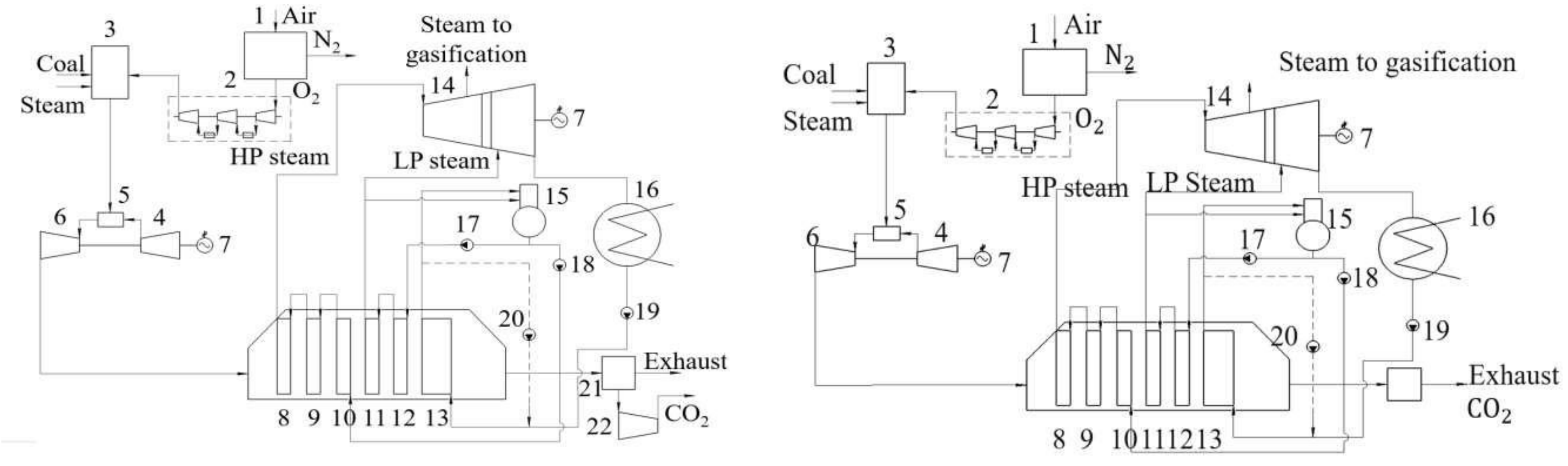
The first TPP type reviewed here is the coal TPP with the coal gasification into syngas (fig.1a) and the CO2 capture. Gasification block 3 transforms coal into syngas. The air split facility (ASF) 1 produces oxygen from atmospheric air and compresses it in the oxygen compressor 2. Steam for the gasification process is taken from the steam turbine 14. Syngas in burned in the combustor 5. Compressor 4 compresses air and sends a part of it to the gas turbine cooling 6. The gas turbine 6 rotates the electric power generator 7. The turbine exhaust gas enters the heat recovery boiler and gives its heat to the steam turbine cycle through the heat exchanger surfaces. Block 21 captures the exit CO_2, the compressor 22 compresses it and sends it to the carbon dioxide storage.

In the steam turbine cycle, pump 19 sends the condenser 16 exit water to the heater 13. Upstream the heater the recirculation pump 20 sends a part of heated water to recirculation. The low-pressure feedwater sequentially passes the low-pressure vaporizer 12, the steam superheater 11, and the steam turbine mixer 14. In the mixer, steam is mixed with high-pressure steam [20].

The high-pressure feedwater is sent to the economizer 10, the high-pressure vaporizer 9, and the steam superheater 8 like in the low-pressure circuit. The high-pressure steam produces electricity in enters the steam turbine 14. The exhaust steam enters the condenser 16.

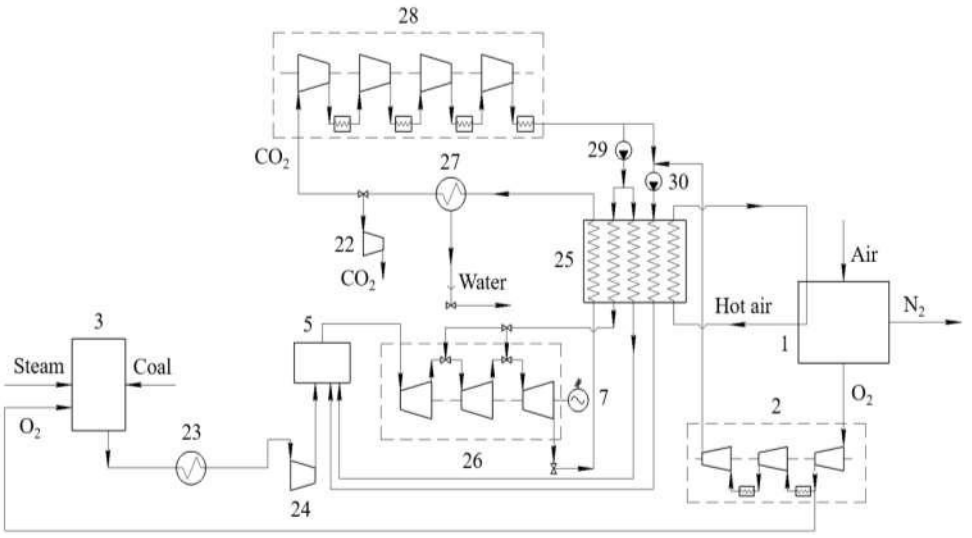
The second facility version (fig. 1b) is the IGCC without capturing. This version differs from fig. 1a by the absence of the elements 21 and 22. After the heat recovery boiler, the exhaust gas with the carbon dioxide content leaves the atmosphere.

The third version (fig. 1c) describes a coal firing TPP with oxygen fuel combustion. Coal gasification block 3 is supplied with coal, oxygen, and steam. The produced syngas is cooled in cooler 23 for a more efficient compression, then compressed in the fuel compressor 24 and sent to the combustor 5. The syngas is burning in the almost pure oxygen produced in ASU 1. The CO_2 heated flow goes to the multi-flow regenerator 25. Downstream the combustor 5 the working fluid enters the carbon dioxide turbine 26. The turbine 26 exhaust enters the multi-flow heat exchanger 25 where it gives its heat to the CO_2 flow, the turbine heat carrier 29 of CO_2 with O_2. The regenerator 25 exhaust enters the cooler-separator 30 where the working fluid water steam condenses. Then the CO_2 flow splits into two parts. The main part is compressed in compressor 28 and the remaining part is compressed in compressor 22 and stored.



a) IGCC with CCS

b) IGCC without CCS



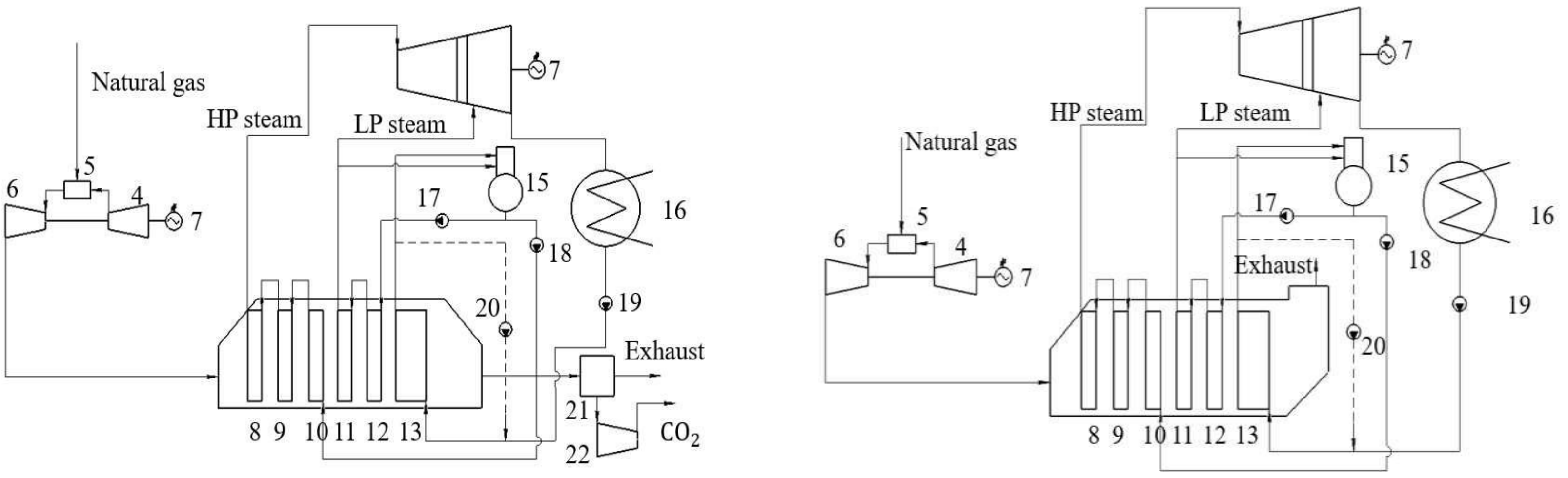
c) Oxy-fuel power plant with coal gasification

Fig.1. Heat flow charts of coal firing TPP with internal coal gasification

After the multi-stage compressor 28, the CO_2 flow is split into two equal parts. One part is mixed with oxygen. After the CO_2 compressor 29, its exit splits into two parts. The smaller part works as the turbine 26 heat carrier and it is heated in the regenerator 28. The regenerator heats the main CO_2 flow and the oxygen-CO_2 mixture. The oxygen-carbon dioxide compressor 30 compresses the mixture up to the maximal temperature acceptable for the regenerator temperature difference. The hot flows that enter combustor 5 from the regenerator 25 reduce the fuel flow needed for the operating fluid heating up.

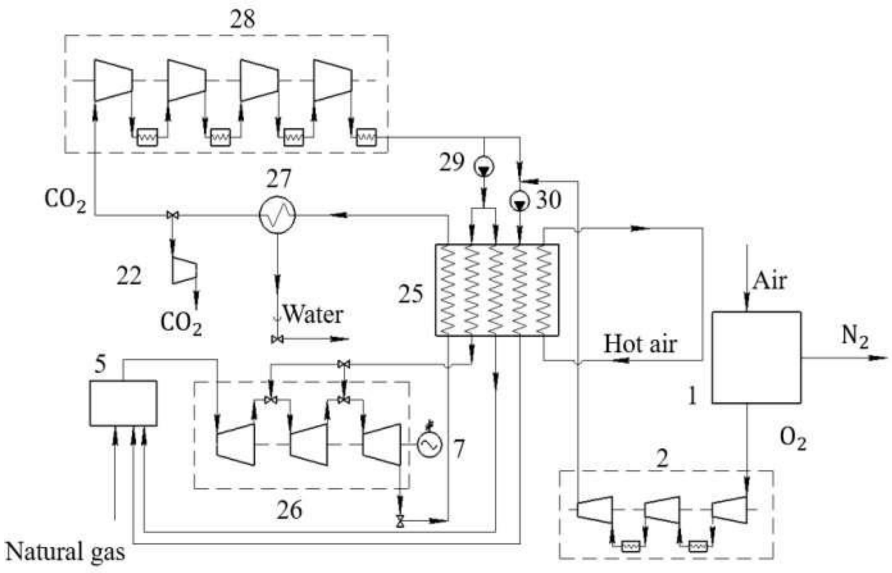
The second type of facility reviewed in this paper is the natural gas firing facilities (fig. 2) [19]. The first type is the NGCC facility with CO_2 capture (fig. 2a). This facility differs from the IGCC type; it has no coal gasification elements 1-3. The second type (fig. 2b) is the NGCC without the CO_2 capture (21, 22).

The third type (fig. 2c) is the oxy-fuel natural gas firing facility that differs from the coal firing with coal gasification (fig. 1b) by the absence of coal gasification elements 1 – 3.



a) NGCC with CCS

b) NGCC without CCS



c) Oxy-fuel power plant

Fig.2. Heat flow charts of natural gas firing TPP

The review of scientific papers and technical reports [21, 22] is devoted to the evaluation of the combined cycle facilities' total carbon footprint. The most significant is the greenhouse gas emission during the facility operation. The mean greenhouse emission during equipment manufacturing, construction, and decommissioning is about 1% of the total emission. The Product Standard [23] method allows not to take into account the life cycle stages that make below 1% of carbon footprint separately and 5% in total. So, the system boundaries are assumed as the following:

- manufacturing and construction stages are not considered;
- the operation stage considered, the carbon footprint analysis includes not only fuel combustion but also fuel mining and shipment;
- the decommissioning and scrap stages are not considered.

2. Initial data

The life cycle carbon footprint analysis input data are given in table 1-3, the considered TPP types are summarized in table 1. Different TPP types are compared at equal net power values. This allows adequate comparison and the relation between the facility efficiency and emissions. The distances from coal or natural gas deposits to TPP are assumed equal to adequately analyze the influence of fuel type upon the TPP carbon footprint at the stages of fuel mining and shipment. Also, in the TPP with internal gasification the assumed fuel is not syngas but coal which is due to the assumed life cycle boundaries.

Table 2 shows the emission data for natural gas and syngas fuels combustion in gas turbine combustors. The emission analysis must take into account the type of fuel-burning equipment. For example, it is known that the natural gas combustion in steam turbine facilities produces lower emissions per kilogram of fuel, than the gas turbine one. Table 3 shows reference initial data for the carbon footprint analysis.

Table 1. TPP parameters

TPP type	Net power, MW	Net efficiency, %	Fuel	Distance from deposit, km	Life, years
NGCC	100	63.50% [20]	Natural gas	3000	20
NGCC with CO_2 and NO_x capture	100	57.10% [20]	Natural gas	3000	20
Oxy-fuel facility	100	46.70% [20]	Natural gas	3000	20
IGCC	100	53.50% [20]	Coal	3000	20
IGCC with CO_2 and NO_x capture	100	46.20% [20]	Coal	3000	20
Oxy-fuel facility	100	36.30% [20]	Coal	3000	20

Table 2. Harmful emissions produced by fuel combustion and Global Warming Potential (GWP)

Fuel	Harmful emission, kg/kg				
	CO_2	CH_4	N_2O	NO_x	SO_2
Natural gas	2.75 [22, 24]	4.0E-04 [22]	1.39E-04 [21, 24]	1.49E-02 [25]	7.0E-07 [22]
Syngas	2.49 [26]	2.67E-04 [26]	2.7E-04 [26]	1.53E-03 [27]	2.14E-03 [27]
GWP (AR6) [9]	1	82.5	273	0	0

Table 3. Reference input data for the carbon footprint analysis

Parameter	Value
CO_2 leakage in an oxy-fuel facility, %	1.0 [18]
TPP annual operation, hr/year	6000 [28]
Coal conversion with gasification, %	95 [29]
Natural gas calorific value, MJ/kg	49 [30]
Coal calorific value, MJ/kg	27 [31]
CO_2 capture efficiency in a NGCC and IGCC, %	89 [20]
SCR NO_x precipitation efficiency, %	95 [15]
Natural gas transportation leakages, %	0.036 [32]
Gas-main pipeline power efficiency, kg gas/ (mln. kg · km)	21.83 [32]
Greenhouse gas emission in coal transportation, kg CO_{2e}/(ton·km)	0.04 [33]
Greenhouse gas emission in coal mining, kg CO_{2e}/kg coal	0.3 [34]

3. Methodology

In this research, complex physical-chemical methods were used to estimate carbon footprint by methods according to GHG standard methodology [11], including stages of fuel mining, fuel transporting and power plant operation. In the operation stage considered fuel combustion only as a main process leading to greenhouse gas emissions during plant operating. To estimate carbon footprint of lifecycle stages material balance physical methods were used. To estimate specific emissions during fuel mining, fuel transporting and combustion were used following data:

1. Empirical and analysis estimated data for fuel mining and transporting according literary [18, 30-34];
2. Combination of empirical physical-chemical data and stoichiometric chemical analysis for combustion according to sources [20-30].

Calculations were provided by using MS Excel 2021. To validate model obtained were used initial data and results described in [21, 22].

Different natural gas and coal firing TPP with internal gasification produce the carbon footprint that may be calculated as the following:

$$E_{sum} = E_c + E_t + E_m, \tag{1}$$

where E_{sum} – total greenhouse gas emission following mining, shipment, and combustion during the power production facility operation, ton CO_{2e};

E_c – total greenhouse gas emission following the combustion during the power production facility operation, ton CO_{2e};

E_t – total greenhouse gas emission following the fuel transporting during the power production facility operation, ton CO_{2e};

E_m – total greenhouse gas emission caused by the fuel mining during the power production facility operation, ton CO_{2e}.

For gas and coal firing TPP with internal gasification E_c is calculated as the following:

$$E_c = \frac{M \cdot T \cdot \sum_{i=1}^{n} e_{gi} \cdot GWP_i \cdot (1-\alpha_c)}{1000}, \tag{2}$$

where M – annual fuel consumption in TPP, kg·year; T – thermal power plant operation life, years;

e_g – specific harmful emission related to the burned fuel, kg/kg; GWP_i – potential global warming caused by the emissions, kg CO2e/kg; α_C – emission precipitation rate, %.

For gas fuel the annual consumption M is calculated by the following equation:

$$M = \frac{N \cdot \tau \cdot 3.6 \cdot 10^6}{\eta \cdot Q_H}, \tag{3}$$

where N – thermal power plant net power,

For coal firing TPP with internal gasification it is necessary to take into account the gasification process efficiency so the coal annual consumption M MW; τ – estimated TPP annual operation, hr; η – net efficiency, %; Q_H – Fuel heating value kJ/kg.is calculated by the following equation:

$$M = \frac{N \cdot \tau \cdot 3.6 \cdot 10^6}{\eta \cdot \eta_g \cdot Q_H}, \tag{4}$$

where η_g – coal gasification conversion rate, %.

The components E_t and E_m in equation (1) are calculated by different equations for different fuels. Gas transportation in main pipelines is usually provided by gas turbine pumping facilities working on the natural gas fuel, so for the transportation stage, the pump driving carbon footprint is taken into account. Also, an important emission factor is the natural gas leakage through seals and control accessories. Usually, these leakages are as small as below 0.05% but methane has high GWP so this factor also should be involved. Besides this, the greenhouse gas emission in production also should include transportation gas consumption. So the natural gas transportation carbon footprint is calculated by the equations:

$$E_t = E_{ct} + E_{lt}, \tag{5}$$

where E_{ct} – total greenhouse gas emission caused by the fuel transporting, by fuel combustion in gas pumping stations during the power production facility operation, ton CO_{2e};

E_{lt} – total greenhouse gas emission caused by the fuel transporting, by fuel leakages during the power production facility operation, ton CO_{2e}.

$$E_{ct} = \frac{M_t \cdot T \cdot \sum_{i=1}^{n} e_{gi} \cdot GWP_i \cdot (1 - \alpha_c)}{1000}, \tag{6}$$

where M_t – amount of the natural gas consumed in the gas pumping facilities, kg/year.

$$M_t = \frac{M \cdot \omega \cdot l}{(1 - \eta_l) \cdot 1000000}, \tag{7}$$

where ω – natural gas specific consumption in gas pumping plants, kg/(mln.kg·km);

l – distance from the fuel mining place to the TPP location, km;

η_l – natural gas leakages in pipelines, %.

$$E_{lt} = \eta_l \frac{(M + M_t) \cdot GWP_{CH4} \cdot T}{(1 - \eta_l) \cdot 1000}. \tag{8}$$

The oxy-fuel power facilities operate a closed cycle with pure oxygen oxidation, so the parameter α_c for NO_x, SO_2, CH_4, and N_2O is assumed as 100% because the emission of these gases is minor and nearly zero. For CO_2 this parameter α_c is assumed 99% for the leakages in the moving device seals of 1% (table 4). The natural gas production carbon footprint is calculated with the equation:

$$E_m = \frac{(M+M_t) \cdot T \cdot \gamma_m}{(1-\eta_l) \cdot 1000}, \tag{9}$$

where γ_m – greenhouse gas specific emission caused by the natural gas mining, kg CO_{2e}/kg.

For coal fuel, E_t and E_m are calculated with statistical mean data on greenhouse emission in coal mining and transportation. The following equation is used for the coal mining carbon footprint:

$$E_m = \frac{M \cdot T \cdot \mu_m}{1000}, \tag{10}$$

where μ_m – greenhouse emission in coal mining, kg CO_2e/kg.

The coefficient μ_m reflects emission of the methane content in coal layers, the greenhouse gas emission by the coal mining machine engines, and the energy consumption by coalfield. The coal transportation carbon footprint is calculated by the following equation:

$$E_t = \frac{M \cdot T \cdot \sigma_t \cdot l}{1000000}, \tag{11}$$

where σ_t – greenhouse emission in coal transportation, kg CO_{2e} /(ton·km).

Here σ_t describes the greenhouse emission by the technology transport that moves coal in operation, for electric transport this coefficient corresponds to the mean emission in electricity production and distribution.

4. Results and discussion

Table 4 summarizes analysis results for the carbon footprint of natural gas firing TPP. Comparison analysis shows that among the considered types the oxy-fuel facility has the smallest greenhouse emission. Its carbon footprint is 49% smaller than the NGCC with CO_2 capture and storage system. This difference is due to the oxy-fuel facility closed cycle and the minimal CO_2 operation leakages. It is worth mentioning that the introduction of the CO_2 capture in NGCC reduces the carbon footprint by 4.6 times in spite of its smaller efficiency. This shows the high CCS potential for the existing TPP modernization.

Table 5 shows the contents of the greenhouse gas and harmful agent emissions. The emission analysis shows that 97.48% of NGCC without CCS emission with consideration of GWP is CO_2. The introduction of the CCS reduces the CO_2 contribution down to 80.99%. This shows that the CH_4 and N_2O emission mitigation may be the trend for the carbon footprint reduction in TPP after the TPP modernization with CCS systems.

Table 6 shows results of the carbon footprint calculation for the syngas firing TPP. It is worth mentioning that the internal gasification TPP overcome the natural gas firing TPP for 2 – 5 times in different TPP types. This is mostly due to the smaller coal energy capacity and the lower TPP efficiency.

Comparison of the coal firing facilities with internal gasification carbon footprint shows that the oxy-fuel facility has the smallest greenhouse emissions among the considered TPP types. The oxy-fuel facility's carbon footprint is 28% smaller than that of the IGCC with CO_2 capture and storage. This is due to the closed cycle of the oxy-fuel facility and minimal CO_2 operational leakage. It is worth mentioning that implementation of the CO_2 capture and storage in an IGCC may 6 times reduce its carbon footprint in spite of the lower efficiency. This shows the high potential of the CCS technology for the TPP with internal gasification.

Table 4. Structure of natural gas firing TPP footprint

TPP type	Carbon footprint, ton CO_{2e}			
	Fuel mining	Fuel transporting	Combustion	Total
NGCC	2 921	297 180	3 915 132	4 215 234
NGCC with CO_2 and NO_x capture	3 248	330 490	576 490	910 228
Oxy-fuel facility	4 138	404 089	51 896	460 123

Table 5. Harmful emission contents by natural gas firing TPP

TPP type	Emission produced in combustion during the operation life, ton					
	CO_2	CH_4	N_2O	NO_x	SO_2	Total, ton CO_{2e}
NGCC	3 816 567	555	193	20635	1	3 915 132
NGCC with CO_2 and NO_x capture	466 878	617	215	1 147	1	576 490
Oxy-fuel facility	51 896	~0	~0	~0	~0	51 896

Table 6. Structure of carbon footprint for the TPP with internal gasification.

TPP type	TPP carbon footprint for 20 years operation, ton $CO_{2\,e}$			
	Fuel mining	Fuel transporting	Combustion	Total
IGCC	964 655	381 545	7 733 119	9 079 318
IGCC with CO_2 and NO_x capture	1 117 078	441 832	1 280 175	2 839 085
Oxy-fuel facility	1 421 736	562 331	109 753	2 093 820

Table 7 presents the greenhouse gas emission structure. In the basic IGCC version, CO_2 makes 96.3% of the carbon footprint with GWP but the CCS technology introduction reduces the CO_2 contribution down to 74.1%. This shows that the CH_4 and N_2O emission mitigation may be a further direction of the facilities' modernization after the CCS system introduction.

Table 7. Contents of harmful emissions from syngas combustion

TPP type	Emissions from fuel combustion for the operation life, ton					
	CO_2	CH_4	N_2O	NO_x	SO_2	Total combustion, ton $CO_{2\,e}$
IGCC	7446 766	799	807	4 577	6 414	7 733 119
IGCC with CO_2 and NO_x capture	948 576	925	935	265	7 428	1 280 175
Oxy-fuel facility	109 753	~ 0	~ 0	~ 0	~ 0	109 753

Conclusions

Comparison of the natural gas and TPP with internal gasification shows that the gas firing TPP has smaller greenhouse gas emissions; the basic IGCC facility produces a 114% higher carbon footprint than the NGCC ones. These differences are due to the low energy capacity of coal, low efficiency of syngas firing facilities, and the high emission of greenhouse gases during coal mining, first of all of CH4. The structure of the TPP carbon footprint has a large part of coal mining. So, the greenhouse emission by mining has to be included in public reports of coal firing companies.

The oxy-fuel facilities have the smallest carbon footprint of gas firing facilities its total greenhouse emission is 49% smaller than in the NGCC with CO_2 capture which shows the oxy-fuel facility's high effectiveness for greenhouse emission mitigation. The NGCC with a CCS system has a 4.6 times smaller carbon footprint than the basic NGCC facility. This shows the high potential of the CCS system for the modernization of the existing power production facilities.

An analysis of TPP with internal coal gasification shows that the oxy-fuel facility has the smallest greenhouse gas emission of the considered gas firing TPP. Its difference with the CCS equipped IGCC is about 28% which demonstrates the smaller effect of the transition to the oxy-fuel facilities in coal fuel than in gas one. The CCS-equipped IGCC has a 6 times smaller carbon footprint than the basic facility which shows a remarkably larger positive effect of CCS introduction than the power production with gas.

The described effects allow the following recommendations:

- application of the oxy-fuel facilities makes minimal carbon footprint, the oxy-fuel introduction in gas firing facilities has higher priority than in the TPP with internal gasification ones;
- modernization of existing TPP by the CCS introduction has high priorities for both coal and gas firing power production, in the second case, positive influence upon the carbon footprint may be higher. Comparison analysis shows that among the considered types the oxy-fuel facility has the smallest greenhouse emission. Its carbon footprint is 49% smaller than the NGCC with CO_2 capture and storage system. This difference is due to the oxy-fuel facility closed cycle and the minimal CO_2 operation leakages. It is worth mentioning that the introduction of the CO_2 capture in NGCC reduces the carbon footprint by 4.6 times in spite of its smaller efficiency. This shows the high CCS potential for the existing TPP modernization.

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