Carbon footprint of the hydrogen production process utilizing subbituminous coal and lignite gasification

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A R T I C L E   I N F O

A B S T R A C T

An analysis was carried out of the carbon footprint (CF) of technology for hydrogen production by subbituminous coal and lignite gasification. The analysis covered entrained flow gasification technology: GE Energy/Texaco and Shell. For calculations, the configuration of the synthesis gas generation system was adopted based on technological solutions available on a commercial scale. Gasification of subbituminous coal using Shell technology gives a yield of 5.1 kg H_2 GJ^{-1} of energy contained in coal. Using the GE/Texaco technology for gasification of subbituminous coal and Shell technology for lignite gasification, hydrogen yields were lower by 8 and 10%, respectively. The scope of the analysis included: mining, mechanical processing, and transport of coal to the gasification plant, as well as gasification and capture of CO_2 and its sequestration. The process of sequestration decreased the CF by 69% for the GE/Texaco technology and 78% for the Shell technology. The CFs of producing 1 kg H_2 with sequestration of carbon dioxide were as follows: 4.1 and 5.2 kg of CO_2 for subbituminous coal gasification using the technology by Shell and Texaco, and 7.1 kg of CO_2 for lignite gasification using Shell technology. The CF per 1 GJ of hydrogen produced in the gasification of subbituminous coal with sequestration of captured CO_2 amounted to 34.5 and 43.4 kg of CO_2 equivalent using the Shell and GE/Texaco technology. This was approximately 2.5 times lower than the CF of 1 GJ of coal. For 1 GJ of hydrogen produced from lignite gasified using Shell technology with sequestration of CO_2, the CF was 59.5 kg of CO_2, about 65% smaller than the CF of 1 GJ of energy in lignite. When the analyzed variations of hydrogen production did not include the sequestration of captured CO_2, the CF of 1 GJ of hydrogen was from 76 to 124% higher compared with the corresponding indicator for coal.

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1. Introduction

Coal is the cheapest primary energy carrier and, unlike oil and gas, its reserves are much larger and located in all major geographical regions of the world (MIT, 2007). World coal reserves are estimated by EUROCOAL (2013) at 750 billion tons, while according to World Energy Council (2009) - 826 billion tons. Coal as well as other fossil fuels - oil, natural gas, bituminous shale is the source of hydrocarbons (Schobert and Song, 2002), which are used for the production of chemicals and specialized carbon materials (Song, 2014).

Currently, more than 50% of coal is used to produce electricity and heat. Coal combustion emits among others NO_x, SO_x, CO_2, which are factors affecting climate change - global warming, environmental pollution and consequently the deterioration of conditions of human life (Guo and Jin, 2013; Agrawal et al., 2007). This negative impact on the environment forces the implementation of so called "clean" coal technologies (Ge et al., 2014). There is a need to develop and refine new high-efficiency, low-carbon technologies for producing electricity and heat from coal. Great hopes are associated with gasification of coal, primarily because of the potentially lower cost of carbon dioxide removal as compared to conventional energy systems based on direct coal combustion (Ge et al., 2013). Coal gasification systems are integrated in a way that, apart from electricity, chemical products are obtained. These include liquid motor fuels, methanol and hydrogen (Collot, 2004; Clayton et al., 2002). The growth of interest in gasification is revealed in the reports of the U.S. Department of Energy and the

National Energy Technology Laboratory (World Gasification Database, 2010). Entrained flow reactors are the most commonly used in new gasification systems. In such reactors, coal or other fuels are fed to the reaction zone in admixture with oxygen and steam. This process may be coupled with the capture, transport and storage of CO_2 (CCS). Among the entrained flow reactors, the GE Energy/Texaco and Shell technologies hold a dominant share in global gas production (Wen et al., 2016). Coal gasification is an effective method of producing hydrogen. It's being considered a key technology in the development of hydrogen economy. Although hydrogen is the most common element in the universe it is not present in large quantities or concentrations on Earth (Stiegel and Ramezan, 2006). Interest in hydrogen as an energy carrier (Kovács et al., 2006) results from its particularly preferred features: hydrogen reacting with oxygen releases a significant amount of energy - 143.1 MJ kg^{-1} and the only reaction product is water (Kapdan and Kargi, 2006). Hydrogen allows direct energy conversion in reaction with oxygen into electricity in fuel cells. Its storage potential is higher than that of the electric current. Hydrogen is also a raw material for many chemical syntheses, both organic and inorganic (Moore and Pearce, 2006). Present world production of hydrogen comes mainly from fossil fuels without CCS from: natural gas and light hydrocarbons (48%) (Wiltowski et al., 2008), refineries/chemical waste gas (30%) (Sun et al., 2012; Wu et al., 2011), gasification of mined coal and biomass (Shen et al., 2008). Remainder is obtained by electrolysis (Zhang and Chen, 2010; IEA, 2007) (18%).

The CF is an objective method of assessing the impact of technology on the environment in terms of greenhouse gases (GHGs) emissions (Andrić et al., 2015; Braschel and Posch, 2013). CF is a measure of the total GHGs emissions, direct and indirect, throughout the life cycle of a product or technology. The methodology used to calculate the CF is the Life Cycle Assessment (LCA), a study of the aspects of potential environmental impacts over the product lifetime. These include its various stages - from obtaining the raw material, through production of the product, to the disposal (Evangelisti et al., 2015; Galli et al., 2012).

In this work we analyzed the CF of the hydrogen production process from subbituminous coal (SBC) and lignite (L) using two gasification technologies: GE Energy/Texaco (GET) and Shell (SH). The emission of CO_2 formed in the hydrogen production cycle was calculated and evaluated. The analysis covered coal mining, mechanical processing, transport of coal to the gasification plant, the process gasification itself and sequestration of captured CO_2. CF analysis was conducted in accordance with the LCA methodology as described in ISO (2014, 2006a, 2006b) standard.

2. Case studies

The CF analysis covered the gasification technologies in an entrained flow reactor for L with the characteristics according to SH technology (Table 1), and for SBC with the characteristics according to GET and SH technology (Table 2). The CF of hydrogen production from coal was calculated according to ISO (2014, 2006a, 2006b) and included following stages: production (mining) of coal, transportation of coal from the mine to the gasification plant, coal gasification and capture of CO_2 followed by its sequestration. It was assumed that the gasification plant is located at the L mine, because moisture content of L is over 50% and its transport is unprofitable. Thus, due to economic reasons it needs to be gasified next to the mine. In case of SBC, which moisture content is only couple percent, it was assumed that, the gasification plant is 100 km from the mine, and that coal is transported by rail. The process of gasification and production of hydrogen was carried out as a single production line with production aimed at maximizing the amount of hydrogen as the main product. For calculations, the configuration of the synthesis gas generation system was adopted based on technological solutions available on a commercial scale: oxygen production system, gasification, hydrogen gas enrichment, desulphurization as well as CO_2 and H_2 (PSA) separation systems. Calculations were performed in the ChemCAD simulator for steady-state processes (v.6.0.2.). Schemes of the processes were shown in Fig. 1 (GET - SBC), Fig. 2 (SH - SBC) and Fig. 3 (SH - L). For the analysis and evaluation of technological variants, the same calculation regimen for electricity production was assumed in each case. It was assumed that the chemical enthalpy of residual gas (leaving the PSA plants) will be converted to electricity with 40% efficiency (the average value for commercially available technologies).

In case of gasification process, the amount of electricity, which must be purchased from outside to cover the auxiliary needs of the plant was taken into account. This situation applied to all examined cases. To calculate the emissions associated with electricity production, which must be purchased for the process — CO_2 emission indicator for electricity production was adopted to 0.9124 kg CO_2 kWh^{-1} for SBC (value for Polish energy mix) and 1.88 kg CO_2 kWh^{-1} for L (value for electricity produced from lignite) (Karcz et al., 2009). Implementation of the hydrogen production process integrated with coal gasification requires the separation of CO_2. As a result, a stream of CO_2 is obtained as a by-product, with the share of more than 99%, which may be a commercial product or can be disposed of. Two scenarios of coal gasification to produce hydrogen were analyzed: (i) production of hydrogen by gasification with the removal of CO_2 without sequestration, (ii) production of hydrogen by gasification with removal of CO_2, its transportation and disposal in geological beds.

For the purpose of sequestration it is necessary to compress the CO_2 separated, then transport and pump it into selected place of geological storage. It was assumed that carbon dioxide would be transported in the liquid phase with the pressure at the inlet of the pipeline of 12 MPa, which would allow for transporting CO_2 at a distance of 120–150 km, and pumping into geological structures without additional compression. Indicator for electricity consumption by CO_2 compression was set at 0.062 kWh per kg CO_2.

Table 1
Characteristics of lignite.

Designation name	As received	Dry	Coal to the reactor
Carbon, %	32.2	64.6	56.9
Hydrogen, %	2.5	5.0	4.4
Nitrogen, %	0.5	1.1	0.9
Total sulfur, %	0.4	0.8	0.7
Oxygen, %	8.0	16.1	14.1
Total moisture, %	50.0	–	12.0
Ash, %	6.3	12.5	11.0
Net calorific value (NCV), MJ kg^{-1}	11.535	25.570	22.202
Gross calorific value (GCV), MJ kg^{-1}	13.343	26.687	23.484

Table 2
Characteristics of subbituminous coal.

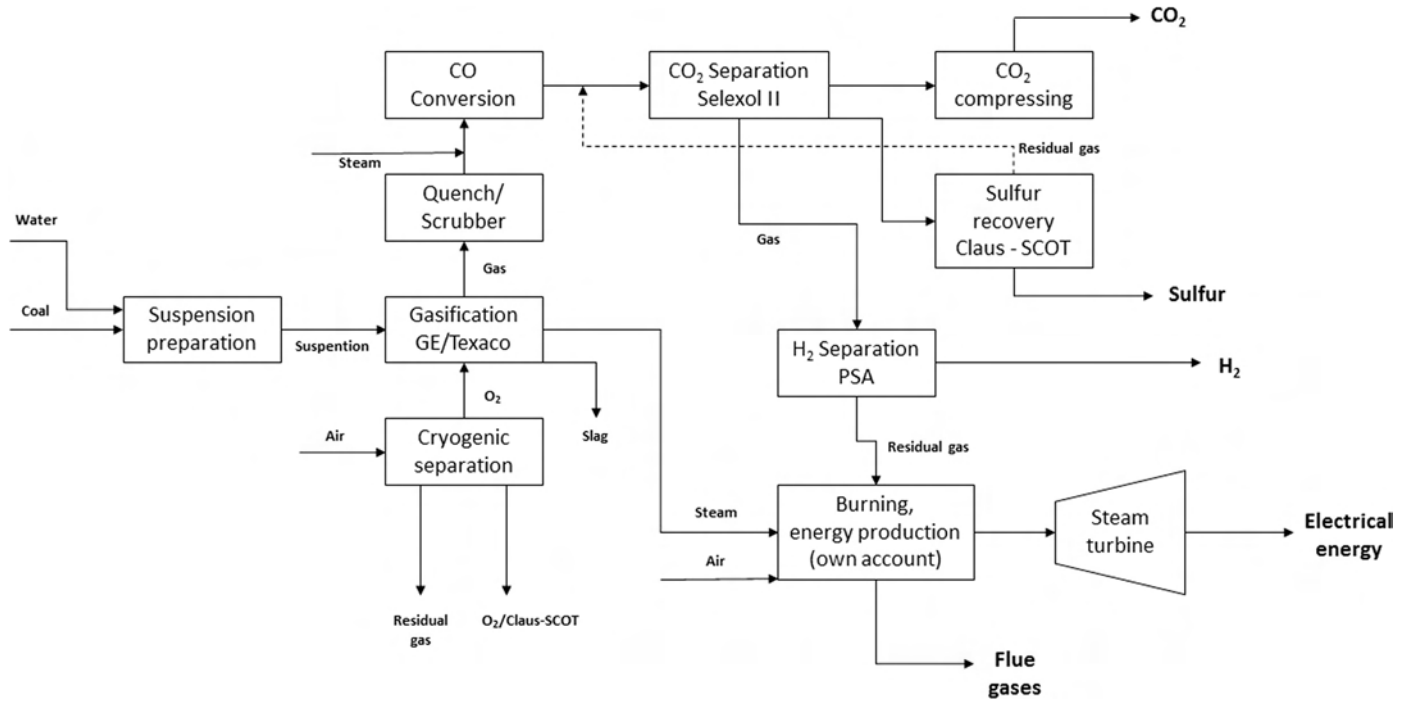| Designation name	As received	Dry	Coal to the reactor
Carbon, %	47.8	59.1	56.1
Hydrogen, %	3.6	4.4	4.2
Nitrogen, %	0.8	1.0	1.0
Total sulfur, %	1.8	2.3	2.1
Oxygen, %	9.4	11.6	11.0
Total moisture, %	19.1	–	5.0
Ash, %	17.5	21.7	20.6
Net calorific value (NCV), MJ kg^{-1}	18.851	23.879	22.560
Gross calorific value (GCV), MJ kg^{-1}	20.134	24.875	23.631

Fig. 1. Process diagram of the GE/Texaco coal gasification and hydrogen production system (subbituminous coal fed in an aqueous suspension).

For the calculations, the consumption of raw coal was assumed to 140 Mg h^{-1} for SBC and 212.5 Mg h^{-1} for L. In case of gasification technology using dry fuel feeding (SH), these values correspond to the comparable mass and energy flows fed to the gasification reactor in the fuel. The adopted efficiencies (in fuel) of the gasification system corresponded to those currently offered to commercial units (Texaco, 1998/2000; Shell, 1998). Another assumption

was that the gasification process would be carried out at the following pressures and temperatures: 5.6 MPa and 1320 °C (GET) and 4.2 MPa and 1400 °C (SH) with the degree of conversion of CO amounting to up to 98% (Chiesa et al., 2005). The efficiency of sulfur and CO_2 removal in the flue gas desulphurization is 99.7% and carbon dioxide removal plant (2-stage SELEXOL technology) is 95% (Chiesa et al., 2005). The efficiency of hydrogen separation for PSA
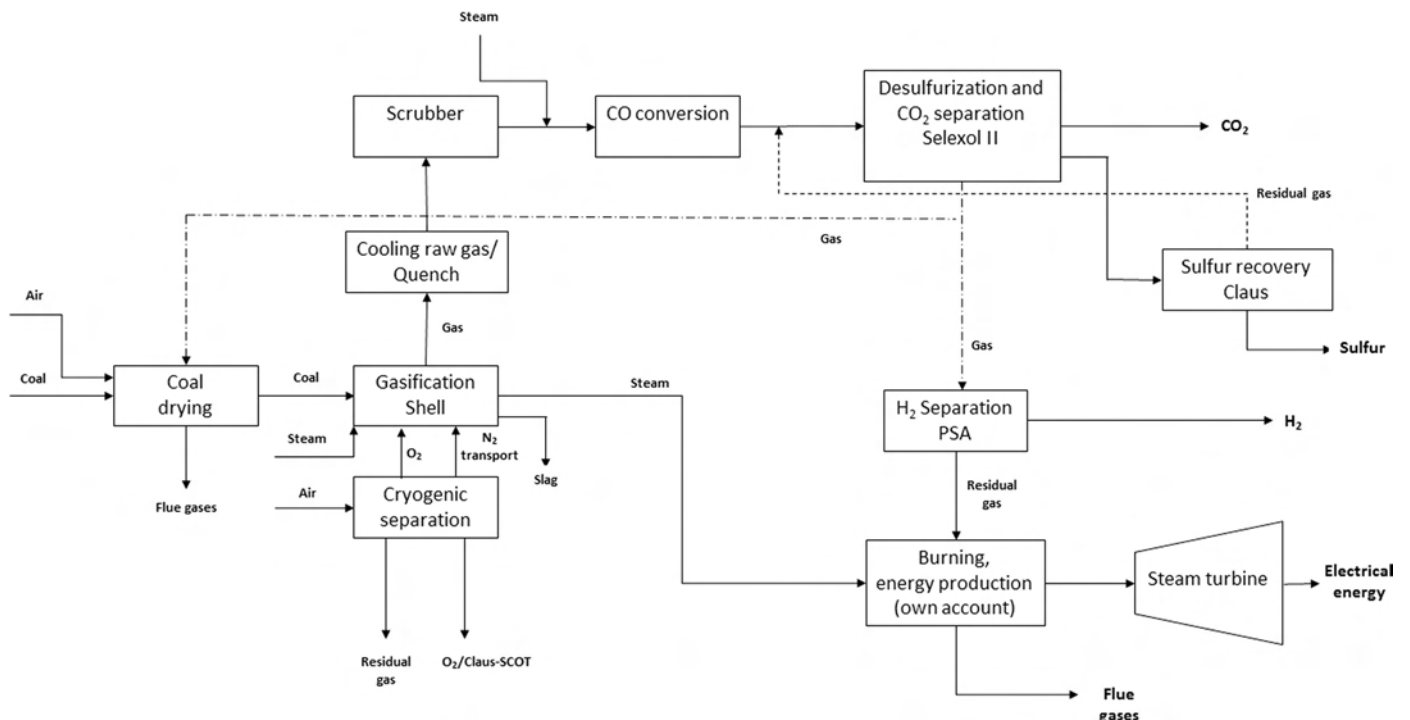

Fig. 2. Process diagram of the Shell coal gasification and hydrogen production system (dry feeding of fuel - subbituminous coal).
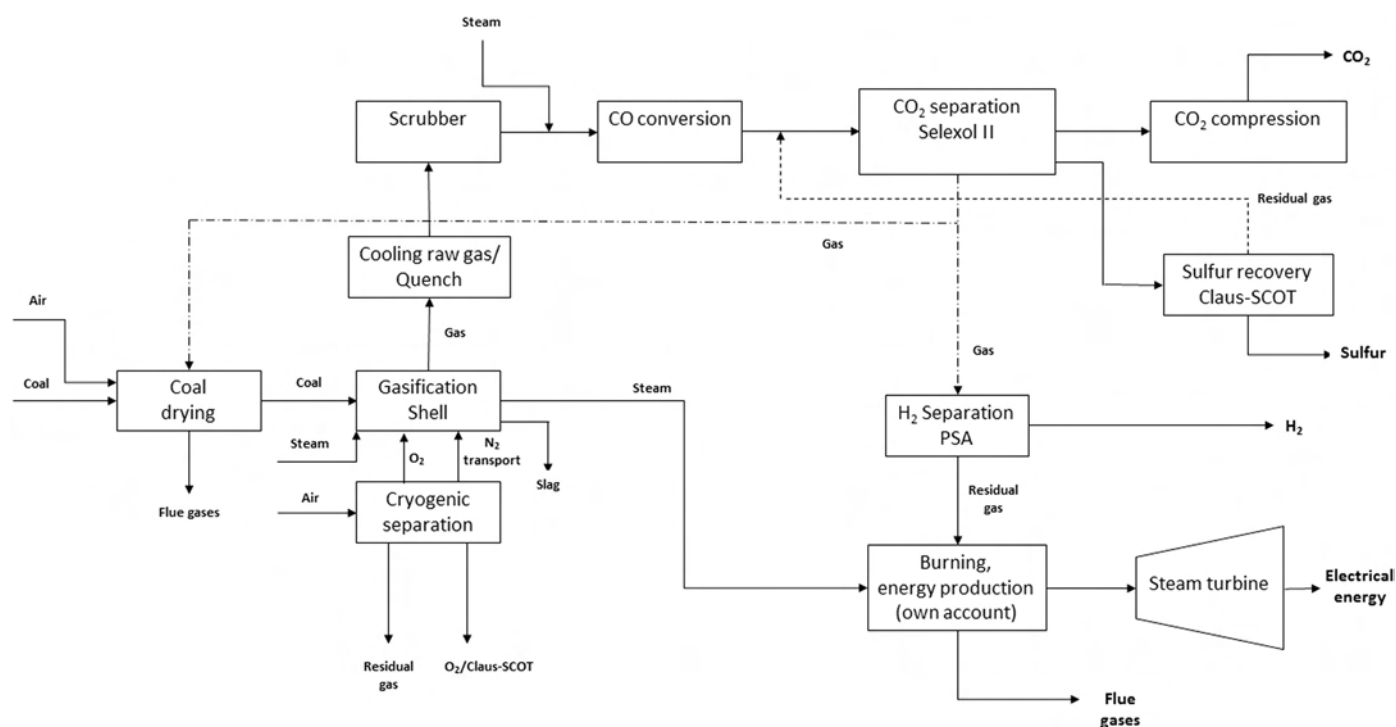
Fig. 3. Process diagram of the Shell coal gasification and hydrogen production system (dry feeding of fuel - lignite).

technology is 86% (Chiesa et al., 2005). Data about the configuration of the hydrogen production system using GET and SH technology were shown in Table 3.

3. Results and discussion

Table 4 summarizes the data describing the coals used, the calculated values of the hydrogen yield values, and conversion efficiency for chemical enthalpy. Table 5 provides a CF summary in kg of the equivalent of CO_2 GJ^{-1} of coals NCV and kg CO_2 kg^{-1} of

hydrogen for all three variants of gasification technology throughout the hydrogen production cycle.

3.1. Comparison of the technologies

Of the three analyzed variants of hydrogen production in the coal gasification process, the most effective technology was the SH process of gasifying SBC. This variant had the highest hydrogen yield value per unit of mass of dry coal to be gasified (118.6 kg H_2 $Mg_{d.c.}^{-1}$), while the hydrogen yield from SBC gasification using

Table 3
Configuration of the hydrogen production systems using GET and SH technology.

Specification	GET, SBC	SH, SBC	SH, L
Production of oxygen	Cryogenic separation	Cryogenic separation	Cryogenic separation
Gasification system			
Reactor	Entrained flow reactor with a fuel fed in an aqueous suspension and a radiation heat exchanger	Entrained flow reactor with dry fuel feeding	Entrained flow reactor with dry fuel feeding
Gasification pressure, MPa	5.6	4.2	4.2
O_2/coal ratio, kg O_2 kg^{-1} of dry coal	0.725	0.648	0.648
Coal conversion rate, %	98.0	99.5	99.5
Calorific value of gas, MJ m^{-3}	7.200	10.173	8.943
Oxidizer	Oxygen (95 vol%)	Oxygen (95 vol%)	Oxygen (95 vol%)
Fuel	Subbituminous coal	Subbituminous coal	Lignite
Share of coal in the suspension fed into the reactor, kg of dry coal kg^{-1} of suspension	0.63	—	—
Moisture content in the fuel fed into the reactor, %	—	5	12
Gas conversion and purification system			
WGS	Yes	—	—
CO conversion	—	Yes	Yes
Desulphurization	1-stage Selexol (99.7%)	1-stage Selexol (99.7%)	1-stage Selexol (99.7%)
Sulfur recovery	Claus/Scot	Claus/Scot	Claus/Scot
Particulate removal	Water quench/scrubber	Water quench/scrubber	Water quench/scrubber
Separation of CO_2	2-stage Selexol (95%)	2-stage Selexol (95%)	2-stage Selexol (95%)
Hydrogen separation system			
Technology	Pressure swing adsorption (PSA)	Pressure swing adsorption (PSA)	Pressure swing adsorption (PSA)
H_2 separation efficiency, %	85	85	85

Table 4
Data characterizing the coals used and hydrogen yield indicators.

Hydrogen production technology system	GET, SBC	SH, SBC	SH, L
Total moisture content, %	19.1	19.1	50.0
NCV, MJ kg^{-1}	18.9	18.9	11.535
Hydrogen yield indicator, kg H$_2$ Mg$_{m.c.}^{-1}$	88.3	95.9	53.5
Hydrogen yield indicator, kg H$_2$ Mg$_{d.c.}^{-1}$	109.2	118.5	107.0
Hydrogen yield indicator, kg H$_2$ GJ^{-1} of coal	4.7	5.1	4.6
Conversion efficiency of chemical enthalpy, %	56.0	60.9	55.5

GET technology was 109.2 kg H$_2$ Mg$_{d.c.}^{-1}$. Gasification of 1 kg of dry L using SH technology allows obtaining 107.0 kg of hydrogen (Table 4). SH technology had a higher degree of conversion of gasified coal (99.5%), compared to the GET technology (98.0%). For this reason, the variant of hydrogen production according to SH technology using SBC had the highest conversion efficiency of chemical enthalpy, which is 60.9% and significantly increases the product yield. This gives the hydrogen yield of 5.1 kg H$_2$ GJ^{-1}. Using the GET technology, 4.7 kg H$_2$ GJ^{-1} was obtained from the same type of SBC, with the conversion efficiency of chemical enthalpy of 56%. A similar conversion efficiency of enthalpy using SH technology for L (55.5%) gave a hydrogen yield of 4.6 kg H$_2$ GJ^{-1} (Table 4).

3.2. Carbon footprint of the analyzed technologies

The CF value in the entire hydrogen production cycle was the lowest for SH technology for SBC gasification. Production of hydrogen using this process with the removal of CO_2 without its sequestration gave the CF value of 19.4 kg CO_2 kg^{-1} H$_2$. The values

of the corresponding indicators for the production of hydrogen using the SH technology from L and the GET technology from SBC were 25.3 kg CO_2 kg^{-1} H$_2$ and 21.7 kg CO_2 kg^{-1} H$_2$, respectively. The share of emissions associated with the production of coal relative to the total emission ranged from 1.9% for SBC to 2.8% for L. The emission generated during transportation was minimal, ranging from 0.2% for SBC to 0.3% for L. The gasification process including auxiliary operations had the biggest share in the CF: 97.0% for L and 97.8% for SBC (Fig. 4). Direct CO_2 emissions had a share between 79% and 84% in the gasification process (Fig. 5). Indirect emissions were linked to consumption of electricity in the following operations: preparation of air and oxygen (11−14%), desulphurization of gas from gasification and recovery of sulfur (2−3%), power supply for water-steam circuits (1.2−1.4%). The consumption of electricity in the remaining operations, such as preparation of coal for gasification, dewatering and transport of slag was lower and its contribution to the CF of the overall gasification process varied around 1%.

The CF of hydrogen production by gasification of coal, calculated according to the LCA methodology, is the sum of direct CO_2 emissions and indirect emissions mostly associated with electricity consumption. The share of direct emissions ranged from 87.1% (SH - L) to 93.6% (SH - SBC). In absolute values, that gave from 18.2 (SH - L) to 22.0 (SH - SBC) kg of CO_2 kg^{-1} of H$_2$. The CF from indirect emissions varied from 1.2 (SH - SBC) to 3.3 kg of CO_2 kg^{-1} of H$_2$ (SH - L). These values consist of indirect emissions associated with net electricity consumption in the gasification process, and electricity consumption associated with the extraction and transport of coal (Fig. 6). Direct emissions are not dependent on CO_2 emission indicators for the production of heat and electricity. In contrast, indirect emissions related mainly to the consumption of electricity

Table 5
Emissions for all three variants of hydrogen production by gasification.

| Emission indicators	kg CO_2 GJ^{-1} of coal			kg CO_2 (kg H$_2$)$^{-1}$		
Hydrogen production technology	GET, SBC	SH, SBC	SH, L	GET, SBC	SH, SBC	SH, L
Coal production	1.94	1.94	3.24	0.416	0.383	0.698
Transport of coal	0.19	0.19	0.35	0.041	0.038	0.075
Purchase of energy, net	8.41	4.17	11.53	1.799	0.821	2.485
Purchase of electricity, net	8.41	4.17	11.53	1.799	0.821	2.485
Purchase of heat, net	0	0	0	0	0	0
CO_2 direct emissions	7.37	8.27	8.66	1.577	1.630	1.867
CO_2 captured (sequestration)	83.49	83.99	93.48	17.870	16.552	20.154
Energy consumption on sequestration	6.41	6.45	9.35	1.373	1.271	2.017
Total emissions without sequestration	101.40	98.56	117.26	21.703	19.424	25.279
Total emissions with sequestration	24.32	21.02	33.13	5.206	4.143	7.142
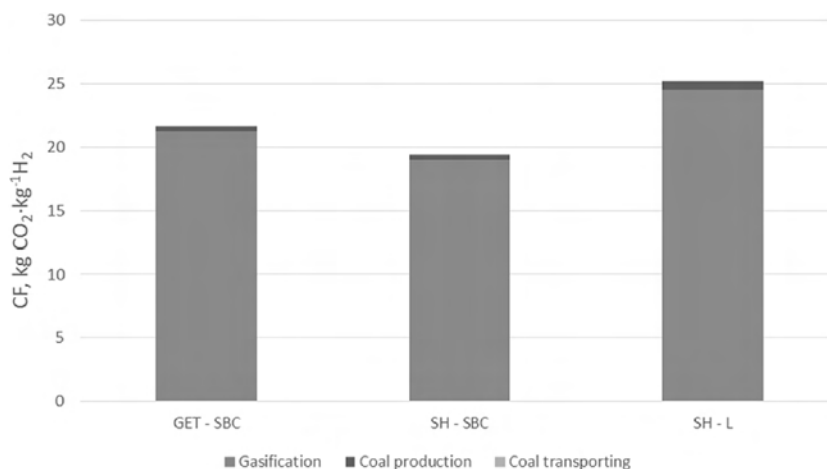
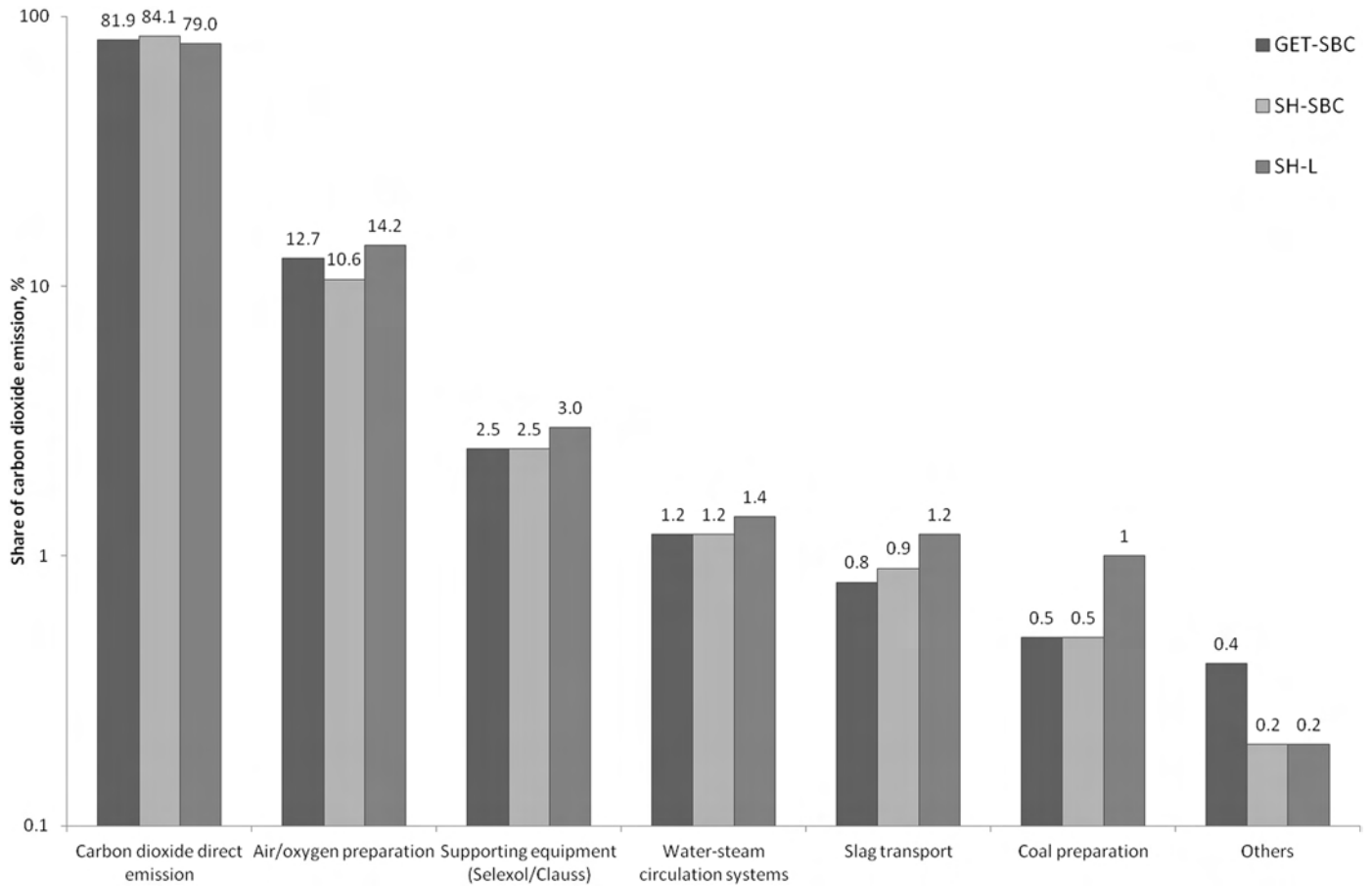**Fig. 4.** CF for the analyzed gasification variants without CO_2 sequestration.

Fig. 5. The share of CO_2 emissions at various stages of the gasification process without CO_2 sequestration.

depend on the CF associated with production 1 kWh. Indicators of such emissions are much larger for countries where energy industry is based on coal, such as Poland. The emission indicators for electricity production are: 0.9124 kg of CO_2 kWh^{-1} for SBC and 1.8800 kg of CO_2 kWh^{-1} for L (Karcz et al., 2009). These values affect the emission indicators calculated for the processes where it is necessary to use external electrical energy.

3.3. Sequestration of CO_2 and the CF of hydrogen production technology

Hydrogen produced using gasification with the removal of CO_2, its transport and disposal in geological beds had much lower emission indicators for all three analyzed variants. For the SH technology, which uses SBC, this indicator was the most favorable
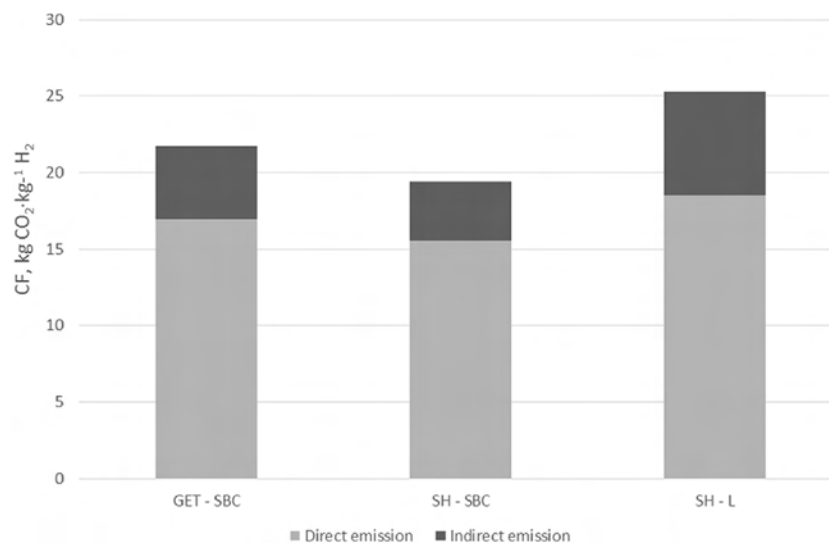

Fig. 6. The CF of the analyzed technologies divided into direct and indirect emissions.
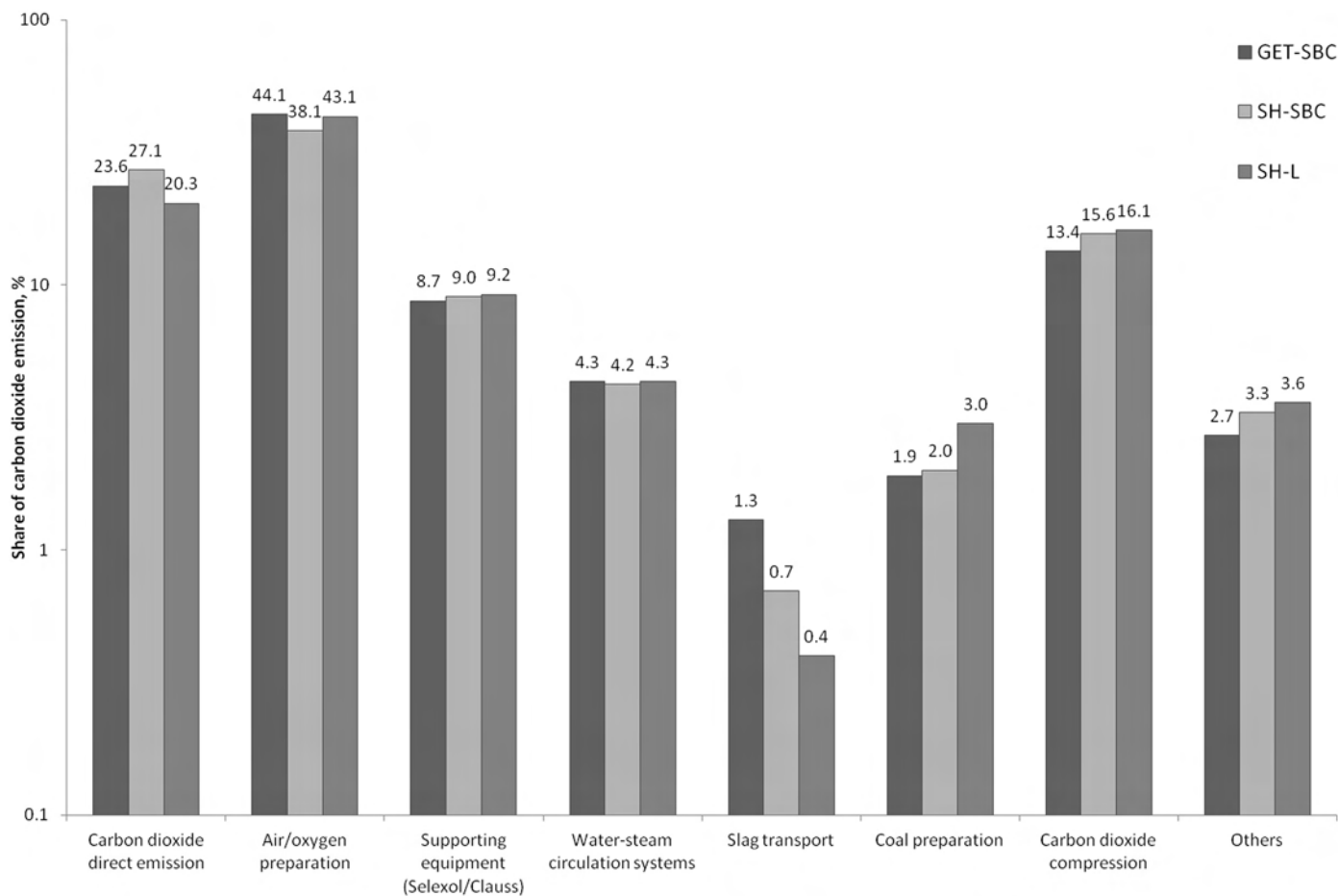
Fig. 7. The share of CO_2 emissions at various stages of the gasification process with CO_2 sequestration.

from the environmental point of view (4.1 kg CO_2 kg^{-1} H$_2$). For L using the same gasification technology, the indicator was 7.1 kg CO_2 kg^{-1} H$_2$. GET technology had a CF at the level of 5.2 kg CO_2 kg^{-1} H$_2$. The use of the sequestration process provided an actual reduction in CO_2 emissions during gasification using all three variants analyzed. The decrease in total equivalent emission of CO_2 was between 69 (GET - SBC) and 78% (SH - L). Sequestration of CO_2 changed the structure of share of the various operations in the total CF. The share of emissions associated with coal mining varied from 8.0 (GET − SBC) to 9.8% (SH - L). Transportation of coal accounted for around 1% of the CF. In contrast, direct emission of CO_2 in the gasification process, together with auxiliary operations was from 1.6 to 1.9 kg CO_2 kg^{-1} H$_2$, which was 26.1–39.3% share in the total value of the CF. Therefore, indirect CO_2 emission associated with electricity consumption was from 60.7% to 73.9% of the CF. In case of SH technology of SBC gasification, the CF related to indirect emission was 2.5 kg CO_2 kg^{-1} H$_2$, of which 1.3 kg CO_2 kg^{-1} H$_2$ fell on indirect emissions resulting from compression of captured CO_2 for sequestration needs. For the gasification variant of L, the CF related to indirect emissions was 5.3 kg CO_2 kg^{-1} H$_2$, of which 2.0 kg CO_2 kg^{-1} H$_2$ was attributable to energy consumption for compressing captured CO_2.

The use of sequestration of the captured CO_2 caused changes in a structure of the CF associated with the gasification process and auxiliary operations (Fig. 7). Direct emissions in the gasification process constituted 20–27% of the CF value compared with that of 79–84% for variant without sequestration. However, the CF

resulting from the process of compressing CO_2 for sequestration had to be added. Its share was around 15%. Among the auxiliary processes, the largest share in the CF of the gasification process constituted preparation of air and oxygen (38–44%), gas desulphurization and recovery of sulfur (around 9%), water-steam cycles (around 4%), preparation of coal for gasification (2–3%). The share of other auxiliary operations did not exceed 3% of the CF associated with the gasification process. If the hydrogen production process was be associated with the process of sequestration, it would become possible to obtain hydrogen as a "low-carbon" fuel in a competitive way in relation to electricity, production of which, is burdened with a large carbon footprint.

The CF calculated for the hydrogen produced by the gasification of SBC with sequestration of captured CO_2 was 34.54 kg CO_2 GJ^{-1} - for the SH technology and 43.41 kg CO_2 GJ^{-1} - for the GET technology. Without the sequestration of captured CO_2, the values of the CF for the SH and GET technologies analyzed were 161.95 and 180.97 kg CO_2 GJ^{-1}, respectively. Comparing these values with the CF for SBC (91.50–91.72 kg CO_2 GJ^{-1}), it can be stated that the production of hydrogen using SBC gasification according to the SH and GET technologies with the sequestration of captured CO_2 generated over 2.5 times lower CF compared to the direct use of SBC.

For L, the CF was 94.3 kg CO_2 GJ^{-1}. Once this L was used for hydrogen production using its gasification according to the SH technology, the CF of 1 GJ of hydrogen were: (i) 59.45 kg CO_2 GJ^{-1} in the case of sequestration of the captured CO_2 and (ii) 210.78 kg CO_2 GJ^{-1} without sequestration.

4. Conclusions

Among the analyzed variants of hydrogen production from L and SBC, the SH technology for gasifying SBC was characterized by the highest yield of the product (5.1 kg H_2 GJ^{-1} coal). For the GET technology of SBC gasification, the same hydrogen yield was 4.7 kg H_2 GJ^{-1} coal, and for the SH technology for L gasification 4.6 kg H_2 GJ^{-1} coal.

The CF of 1 kg of hydrogen, calculated according to the LCA methodology, were: (i) 19.4 kg $CO_{2\text{-e}}$ kg^{-1} H_2 for the SH technology for gasifying SBC, (ii), 21.7 kg $CO_{2\text{-e}}$ kg^{-1} H_2 for the GET technology for gasifying SBC, and (iii) 25.3 kg $CO_{2\text{-e}}$ kg^{-1} H_2 for the SH technology for gasifying L. The use of sequestration of the captured CO_2 decreased the CF of 1 kg of hydrogen produced from 72 (SH - L) to 79% (SH - SBC) as compared to variants without sequestration.

When the CO_2 available for capturing was not sequestered, the CF with respect to 1 GJ of energy contained in hydrogen was from 75 to 124% higher than that of 1 GJ of chemical energy contained in coal. Sequestration of captured CO_2 resulted in lowering CF of 1 GJ of chemical energy in hydrogen well below CF of 1 GJ of chemical energy in coal.

The share of direct emissions in the CF of 1 kg of hydrogen produced in coal gasification without sequestration of the CO_2 available for capturing is between 87.1% (SH - L) and 93.6% (SH - SBC). In case of CO_2 sequestration, indirect emissions begin to dominate. Their proportion ranges from 60.7 to 73.9% of the total value of CF. The most important component of indirect emissions was the electricity consumption used for compressing the captured CO_2. The CF of this component ranged from 1.217 kg $CO_{2\text{-e}}$ kg^{-1} H_2 for the SH technology for gasifying SBC to 2.017 kg $CO_{2\text{-e}}$ kg^{-1} H_2 for the same technology for gasifying L, which is 30.4 and 28.2% of the total value of the CF, respectively.

For variants with sequestration, the CF values assigned to 1 kWh of electricity had large impact on the CF value of 1 kg of hydrogen produced. For countries where energy is based on coal and lignite, the CF of the produced hydrogen is charged with high emission values associated with the generation of electricity and/or heat.

Acknowledgements

Subscripts

d.c.	dry coal
e	equivalent
m.c.	moisture coal

Abbreviations

CF	Carbon footprint
GCV	Gross calorific value
GET	GE Energy/Texaco
GHG	Greenhouse gases
L	Lignite
LCA	Life Cycle Assessment
NCV	Net calorific value
PSA	Pressure swing adsorption
SBC	Subbituminous coal
SH	Shell
WGS	Water gas shift

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