Journal of Sustainable Mining
e-ISSN 2300-3960 | p-ISSN 2300-1364

The online version of the *Journal of Sustainable Mining* is the primary, reference version of the journal

**JOURNAL HOMEPAGE**
jsm.gig.eu

Czaplicka-Kolarz K., Korol J., Ludwik-Pardała M., Ponikiewska K. (2014). Material and Energy Flow Analysis (MEFA) of the unconventional method of electricity production based on underground coal gasification. *Journal of Sustainable Mining*, *13*(3), 41–47. doi: 10.7424/jsm140307

**ORIGINAL PAPER**

**Received**: 22 October 2013 **Revised**: 10 September 2014 **Published online**: 27 October 2014

# MATERIAL AND ENERGY FLOW ANALYSIS (MEFA) OF THE UNCONVENTIONAL METHOD OF ELECTRICITY PRODUCTION BASED ON UNDERGROUND COAL GASIFICATION

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## ABSTRACT

| | |
|---|---|
| **Purpose** | In this paper, the application of Umberto NXT LCA software to devise a Material and Energy Flow Analyses (MEFA) for the technology of producing electricity from gas extracted in the process of shaftless underground coal gasification is presented. The Material Flow Analyses of underground coal gasification includes a range of technology, through obtaining process gas and its purification, to electricity production, and, additionally, the capture of carbon dioxide. |
| **Methods** | To evaluate electricity production based on Underground Coal Gasification, Material and Energy Flow Analyses (MEFA) was used. Modeling material and energy flow helps a high level of efficiency or technology of a given process to be reached, through the effective use of resources and energy, or waste management. The applied software for modeling material flow enables, not only, the simulation of industrial processes, but also the simulation of any process with a material or energy flow, e.g. in agriculture. |
| **Results** | MEFA enabled the visualization of material and energy flow between individual unit processes of the technology of electricity production from UCG gas. An analysis of material and energy flow networks presented in the form of Sankey diagrams enabled the identification of unit processes with the biggest consumption of raw materials and energy, and the greatest amount of emissions to the environment. |
| **Practical implications** | Thanks to applying material and energy flow networks with Umberto software, it is possible to visualize the flow of materials and energy in an analyzed system (process/technology). The visualization can be presented in the form of an inventory list of input and output data, or in the form of a Sankey diagram. In the article, a Sankey diagram has been utilized. MEFA is first stage of the plan to conduct analyses using Umberto software. The analyses performed so far will be used in the following stages of the research to assess the environmental impact using the LCA (Life Cycle Assessment) technique, to analyze costs using the LCC (Life Cycle Cost) technique, and to analyze eco-efficiency. It is important to highlight the fact that this is the first attempt of material and energy flow analysis of electricity production from UCG gas. |
| **Originality/ value** | This is the first approach which contains a whole chain of electricity production from Underground Coal Gasification, including stages of gas cleaning, electricity production and the additional capture of carbon dioxide. |

**Keywords**
*Material Flow Analyses, underground coal gasification, electricity production, Umberto NXT LCA*

## 1. INTRODUCTION

### 1.1. Underground coal gasification (UCG)

Energy security in Poland is based on hard coal, therefore there are developmental, innovative and more effective methods of coal conversion into energy (Stańczyk, 2008). One of the unconventional methods of energy production is gaseous product combustion derived from the underground coal gasification (UCG) process.

The UCG process relies on direct coal conversion, (in-situ) within the coal seam, into a valuable gaseous product – the process gas – which is applicable to energy and heat conversion or chemical synthesis. The technology of underground coal gasification, compared with other methods of processing raw material into energy, is very attractive from the point of view of investment costs, as it does not require building a large production installation. Additional advantages of UCG technology are the environmental aspects, such as the lack of solid waste (ash and slag), and lower emission of exhaust gases into the air (Kapusta & Stańczyk, 2011; Smoliński, Stańczyk, Kapusta, & Howaniec, 2012; Smoliński, Stańczyk, Kapusta, & Howaniec, 2013; Kapusta, Stańczyk, Wiatowski, & Chećko, 2013). The process of UCG can be conducted using one of two methods: the shaft method – through accessing a coal seam from the already existing coal mine shafts and galleries, and the shaftless method – through accessing a coal seam with boreholes drilled from the surface (Ludwik-Pardała & Niemotko, 2012; Stańczyk et al., 2012; Wiatowski et al., 2012). As a result of research conducted so far, both on a pilot scale and a commercial scale, three main groups of underground coal gasification methods which differ in the method of accessing a coal seam, were devised (Stańczyk et al., 2011). In the first group, the shaft method relied on new boreholes drilled in to the seam, or making use of preexisting boreholes in order to connect generators with surface system injecting gasification agents and extracting products through shafts or vertical boreholes. In this group there are two concepts which have been under development in China since 1986:

1. Underground Coal Gasification (UCG),
2. A process making use of long tunnels and large sections.

According to concept 1, parallel blind boreholes are drilled in to a seam perpendicular to a roadway. The boreholes inject a gasification agent using an injection pipe and then extract process gases. Gasification is conducted in the boreholes, until the coal deposit in the drilled area is exhausted. This method is used mainly in horizontal seams. According to concept 2, two parallel galleries are joined with a flue. The galleries can be used, alternately, to inject gasification agents and extract the final product. The gasification front advances perpendicularly to the galleries and towards the shafts, or boreholes, which connect the generator with the surface. The method is applicable, mainly, in inclined seams and originates from experience gained from experiments conducted in the former Soviet Union.

In the other method, shaftless technology, the coal seam for gasification is accessed through vertical holes which form a grid. Some of the holes are designed to be injection wells for a gasification agent while others are used as production wells. The appropriately organized exploitation of the boreholes enables the exploitation of the seam in a systematic manner. The main problem with this method is linking an injection well and a production well to obtain porosity which will enable the flow of the gases through the coal. The methods used, i.e. burning by compressed air pressure, the breaking up of coal with water (hydro-fracturing), and electrocarbonization, are not highly efficient or effective, and can be used only at a limited distance between the boreholes. These methods were used in the former Soviet Union, and they were also exploited in Chinchilla, Australia between 1999 and 2003. There is a third group of state of the art methods which are based on accessing coal seams using directional drilling which originates from the oil and gas drilling industry. The CRIP method (Controlled Retractable Injection Procedure), in which it is possible to use a grid of directionally drilled boreholes, where the combustion front (gasification generator) advances towards injection wells (counter current circulation), is a characteristic representative of the group.

Most experiments employ the shaftless method, as it is believed that the shaft method is devised for the exploitation of residual coal seams in non-operational collieries, where the existing infrastructure enables the exploitation of the remaining coal. Most UCG experiments using the shaftless method were conducted in the USA – over 30 pilot experiments. At present there are two operational commercial installations using UCG process gas for electricity production: in Majuba, The Republic of South Africa, and in Angren, Uzbekistan (since 1955). The UCG process gas application mainly results in energy and heat production as a result of its low calorific value. The calorific value of process gas depends on a number of factors, e.g. the quality of coal, and the kind of gasification agents (Friedmann, 2011). Due to the costs involved the most commonly used agent is air, or oxygen enriched air, which enables the gas of $Q_i$ = 4–6 MJ/m$^3$ to be obtained. When coal is gasified with oxygen only, the costs of the process increase significantly, yet the gas obtained has a higher calorific value, and a higher content of carbon dioxide. When coal is gasified using steam, the obtained gas is rich in hydrogen, which improves its calorific value. The Central Mining Institute conducts research into the UCG, both on a laboratory scale and a pilot scale, with the aim of obtaining gas with high hydrogen content (Stańczyk et al., 2010). The detailed characteristics, and a review of the methods of underground coal gasification, as well as the possibility of employing the technology in Polish conditions are presented in the following pieces of work (Ludwik-Pardała & Niemotko, 2013; Kapusta, & Stańczyk, 2009).

In the following article the shaftless UCG gasification technologies using air were analyzed. The gas obtained after purification was combusted in a combined cycle gas turbine (CCGT)/a gas boiler with steam circulation, into energy production. Figure 1 shows a scheme of the analyzed UCG technology, without the capture of $CO_2$, Figure 2 with the capture of $CO_2$.

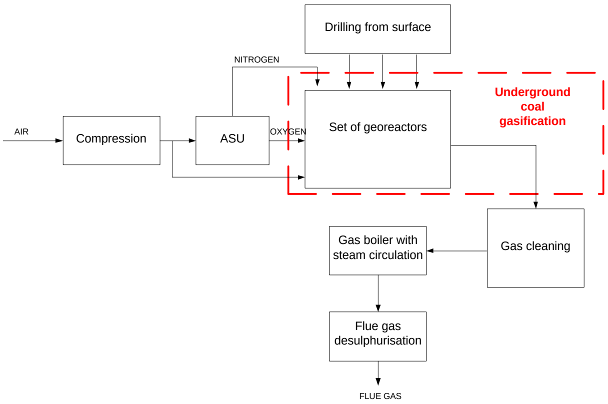

**Fig. 1.** A scheme of the analyzed technology of UCG using a non-shaft method, without the capture of $CO_2$

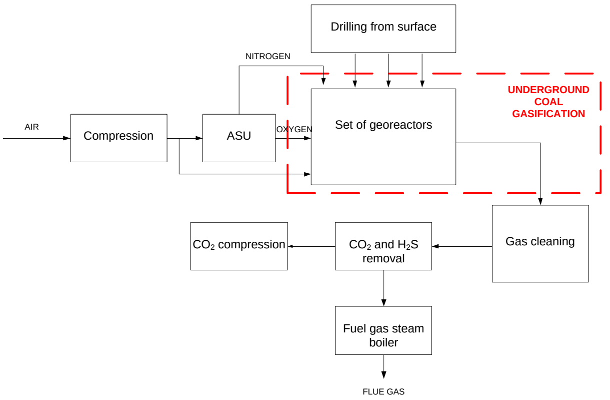

**Fig. 2.** A scheme of the analyzed technology of UCG using a non-shaft method, with the capture of $CO_2$

### 1.2. Umberto for Eco-efficiency software

Umberto software enables material and energy flow analyses (MEFA), Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to be conducted. Thanks to this, it is possible to calculate the eco-efficiency of the analyzed technology or product (Wohlgemuth, Page, & Kreutzer, 2006). In this paper, Umberto for Eco-efficiency software was used for the material and energy flow analysis. In the previous articles, the evaluation of eco-efficiency, and selected eco-efficiency determinants of UCG were presented (Czaplicka-Kolarz, Burchart-Korol, Śliwińska, Krawczyk, & Ludwik-Pardała, 2011; Czaplicka--Kolarz, Burchart-Korol, & Krawczyk, 2013; Burchart-Korol, Korol, Czaplicka-Kolarz, & Krawczyk, 2013).

Modeling a material flow helps a high level of efficiency of a given process or technology to be reached, through the effective use of resources and energy, or waste management. The applied software for modeling material flow enables not only the simulation of industrial processes, but, also, the simulation of any processes with material or energy flow, e.g. in agriculture. Yet, it is important when having such unlimited capabilities, to determine, at the very beginning of the building of a model, the aim of the analyses and boundaries of the predefined system (Buhner, 2013).

Material flow networks are a special form of Petri net and they may be used to model material and energy flow in processes consisting of a large number of unit processes, by considering their impact on the natural environment where the given process takes place (Wohlgemuth et al., 2006).

Thanks to applying a flow network with Umberto software, it is possible to visualize the flow of materials and energy in an analyzed system (process/technology). This visualization can be presented in the form of an inventory list of input and output data, or in the form of a Sankey diagram. Applying Sankey diagrams enables the visual analysis of a given system to be carried out. The thicker the arrow is, the bigger the flow is. In complex chains of technology, consisting of many unit processes, the analysis of a material or energy flow network, in the form of Sankey diagrams, allows for the location of extreme flows. In this way, it is possible to modify a given unit process to limit its energy consumption, or reduce the emission of pollutants (Buhner, 2012).

## 2. METHODOLOGY

In this article, material and energy flow networks created by the technology of electricity production from syngas extracted in the process of shaftless UCG were presented. For this purpose material and energy flow analyses with Umberto NXT LCA software was carried out.

Conducting the analyses required the following stages:

1. Determining the aim and scope of the analyses, and then system boundaries
2. Determining unit processes (transitions) considered within the system (materials and energy are processed/transformed in transitions)
3. Determining the input and output (places) considered within the boundaries of the system
4. Building a material flow network – including transitions, places, connections, and arrows
5. Data inventory LCI (Life Cycle Inventory) – entering data concerning the places and transitions
6. Determining assumptions and the functional unit
7. Calculating material and energy flow
8. Modeling the flow
9. Building a Sankey diagram.

Material and energy flow networks, modeled with Umberto software, consist of transitions, places and arrows. Graphic forms of the elements are presented in Figure 3.

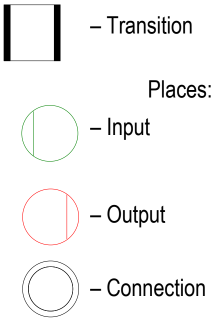

**Fig. 3.** A graphic representation of flow network elements

Each of the elements of a flow network plays a different role/function there (Wohlgemuth et al., 2006):

- Transitions – unit processes; in a flow network they are presented as squares, materials and energy are processed/transformed in transitions, they represent unit processes in a given system.
- Places – three types of places are distinguished: input, output, and connections. Input and output are presented as circles in a flow network. Input characterizes everything that enters a given system from the environment/outside. Output is everything that leaves the system and goes outside to the environment. Input and output are the places which link the system with the environment. In flow networks, connections are presented as two concentric circles. Connections are located between transitions, they are "buffers/reserves", which are successively used and replenished by the flow. They link individual unit processes in an analyzed system if there is no storage stage between the unit processes. The output of one unit process is matched by the input of another unit process, or unit processes.

- Arrows – they connect places and transitions, building the structure of a material and energy flow network. They show the flow, and how much material and energy is transported between places and transitions.

## 3. RESULTS AND DISCUSSION

The aim of this article was to present the material and energy flow network across the whole chain of technology in electricity production from UCG gas; from preparing the seam, to coal gasification, to the purification of the process gas, to electricity production, and, depending on the analyzed variant capture of $CO_2$. For the analyses the technology of electricity production based on shaftless UCG was selected.

The function of the analyzed system is the production of electricity from coal using non-shaft underground coal gasification technology. The functional unit was 1 MWh (net) of produced electricity. Within the boundaries of the system, we considered the whole chain of technology used in underground coal gasification, from drilling boreholes, which inject a gasification agent and extract gasification products, to the process of gasification and purification of the UCG gas, to electricity production, and, depending on the analyzed variant capture of $CO_2$.

### 3.1. Assumptions regarding the analyzed technology of electricity production based on UCG

The first experiment consisted of underground coal gasification using a non-shaft method, conducted with CRIP technology at a depth of 400 m. The experiment was based on there being 9 boreholes of 400 m drilled in to the coal seam with a thickness of 5 m. It was assumed, that during the process of underground coal gasification 42,500 kg/h of process gas with a calorific value of 5 MJ/m$^3$ from 10 000 kg/h of coal would be obtained. The process of gasification was conducted by injecting air. It was assumed that at the initial stage of the gasification process, oxygen released during the process of separation in the Air Separation Unit (ASU) would be used to ignite the underground reactor. Raw gas from the process of gasification was initially purified in the wet scrubber to remove solid waste (dust, particles) and water-tar condensate. The UCG gas was then combusted in a combined cycle gas turbine (CCGT)/gas boiler using steam circulation to produce electricity. The assumed operating time of the installation was 8,760 hours.

The functional unit used for the calculation of material and energy flow analyses was 1 MWh of electricity from UCG gas.

In the second experiment, the assumptions are the same as in the first, but UCG is conducted with the capture of $CO_2$.

Raw gas from the process of gasification was initially purified in a wet scrubber, to remove solid waste and water-tar condensate. The removal of $CO_2$ from the gas would be carried out using SELEXOL technology (NETL, 2011), in which the gas would also have all of the sulphur extracted from it. Purification, initially with a wet scrubber to remove pollutants, i.e. tar, water and dust, followed by the removal of $CO_2$ and $H_2S$ with SELEXOL. The process gas after purification was combusted in a combined cycle gas turbine (CCGT)/gas boiler using steam circulation. The assumed operating time of the installation is 8,760 hours.

Table 1 shows the elements considered in the material and energy flow analyses.

**Table 1.** Elements considered in the material and energy flow analyzes of electricity production from UCG gas, based on self-analyzes and the NETL Report (NETL, 2011)

| TRANSITIONS | PLACES | |
|---|---|---|
| | INPUT | OUTPUT |
| Air Separation (ASU) | Compressed air<br>Electricity "own" | Oxygen<br>Nitrogen<br>Exhaust gas |
| Underground Coal Gasification (UCG) | Coal (in ground)<br>Compressed air<br>Oxygen | Raw gas<br>Heat and energy losses |
| Raw Gas Purification Wet Scrubber | Raw gas<br>Electricity "own"<br>Water | Initially purified gas<br>Waste water<br>Tar |
| Desulphurisation[*] | Exhaust gases<br>Electricity "own" | Exhaust gases and the emission of $CO_2$, $NO_2$, $SO_x$ |
| Acid Gases Removal and $CO_2$ Compression[**] | Initially purified gas<br>Steam<br>Electricity "own" | Compressed $CO_2$<br>Purified gas<br>$H_2S$ |
| Electricity Production | Purified gas<br>Air | Net electricity<br>Heat and energy losses<br>Electricity for "own" use<br>Exhaust gases and the emission of $CO_2$, $NO_2$, $SO_x$ |

[*] For the chain of technology of UCG without the capture of $CO_2$.

[**] For the chain of technology of UCG with the capture of $CO_2$.

In Figures 4, and 5, there is a model network (elements considered within the system's boundaries) of technology and electricity production from UCG gas, with and without the capture of $CO_2$. The functional unit used for the calculation of material and energy flow analyses was 1 MWh of electricity from UCG gas.

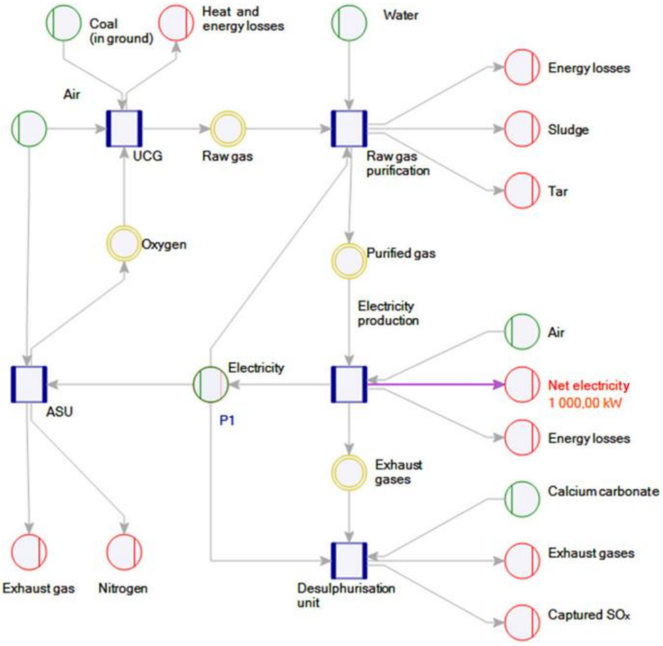

**Fig. 4.** A model of the technology of the production of electricity from UCG gas, without the capture of $CO_2$

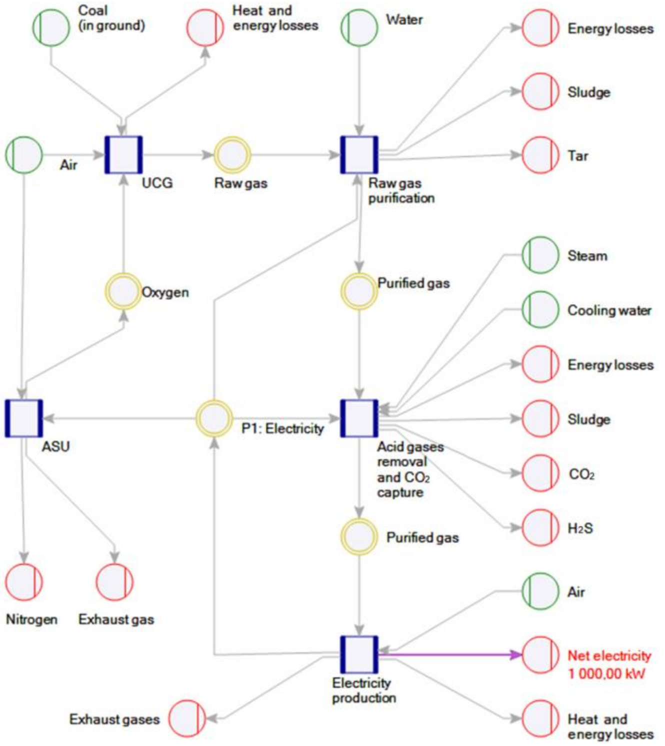

**Fig. 5.** A model of the technology of the production of electricity from UCG gas, with the capture of $CO_2$

Based on the input and output data inventory and taking into consideration the functional unit in the calculations, Sankey diagrams were devised (Fig. 6–9). The energy flow network for the technology of electricity production from ground based coal gasification is presented in the following piece of work (Burchart-Korol et al., 2013a).

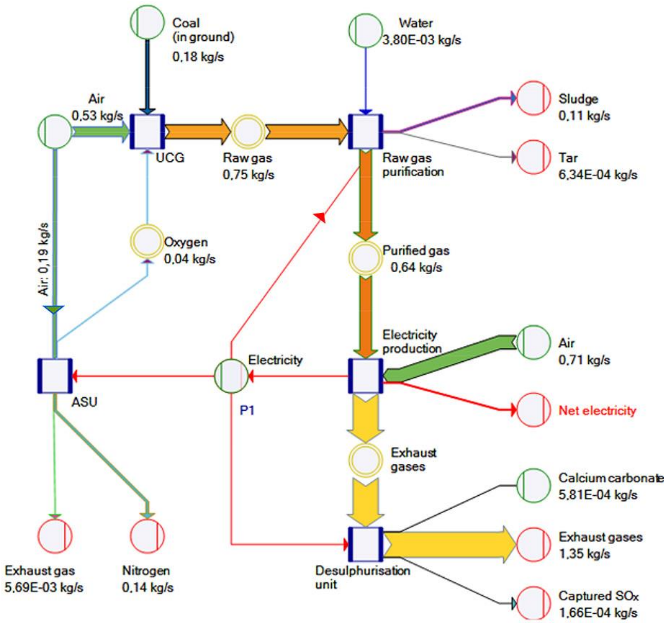

**Fig. 6.** Material flow network of technologies producing 1 MWh electricity from UCG gas, without the capture of $CO_2$, in the form of a Sankey diagram

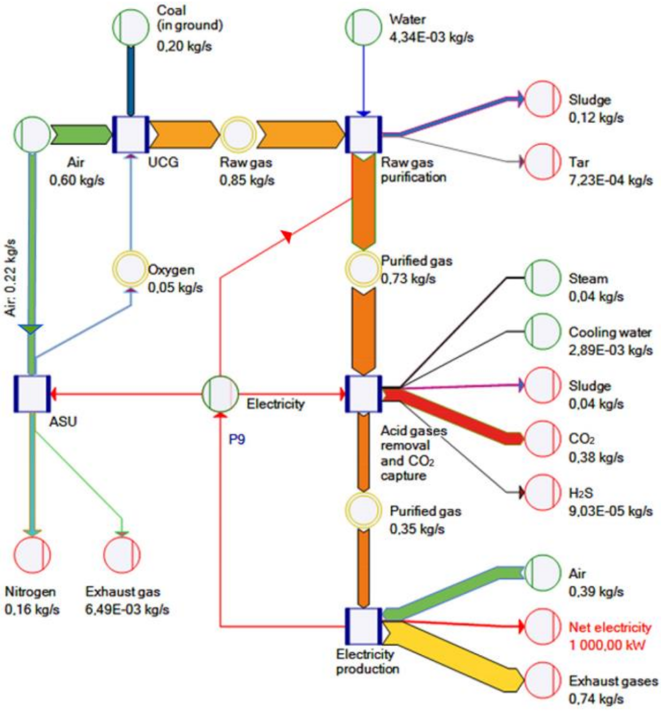

**Fig. 7.** Material flow network of technology of producing 1 MWh of electricity from UCG gas, with the capture of $CO_2$, in the form of a Sankey diagram

Analyzing the material flows for the technology of producing electricity from UCG gas, with and without the capture of $CO_2$, in the form of Sankey diagrams (Fig. 6, and 7), it was shown that there are only slight differences between the analyzed experiments referring to the flow of materials used, or processed, to produce 1 MWh, but the experiment without $CO_2$ capture consumes less fuels. In the experiment without the capture of $CO_2$, there is also a significantly greater amount of emissions of exhaust gases than in the experiment with $CO_2$ capture.

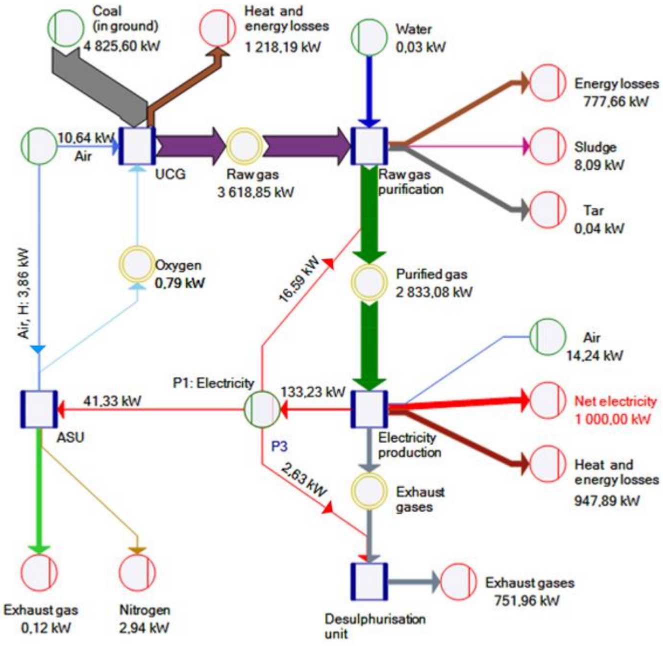

**Fig. 8.** Energy (enthalpy, electricity) flow network of the technology producing 1 MWh of electricity from UCG gas, without the capture of $CO_2$, in the form of a Sankey diagram

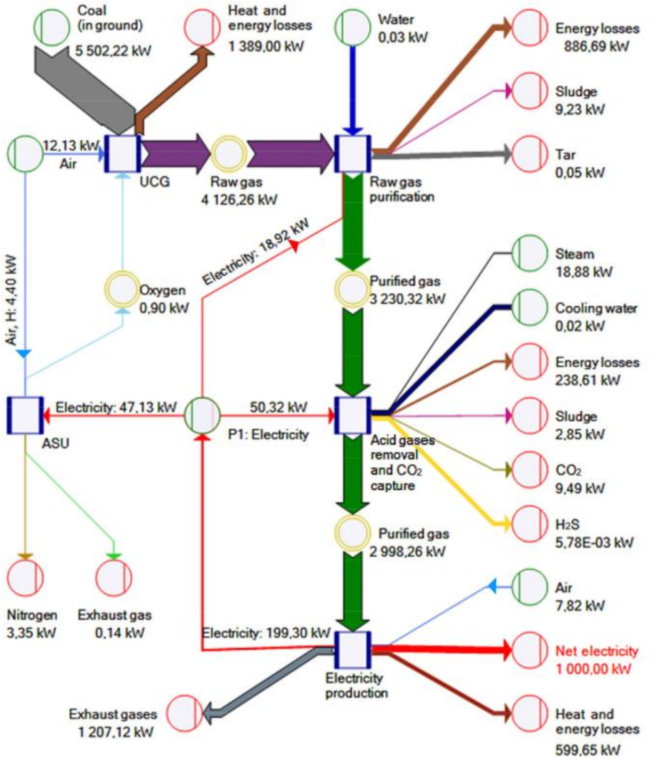

**Fig. 9.** Energy (enthalpy, electricity) flow network of the technology of producing 1 MWh of electricity from UCG gas, with the capture of $CO_2$, in the form of a Sankey diagram

When analyzing the energy (enthalpy, electricity) flows for the technology of electricity production from UCG gas, with and without the capture of $CO_2$, in the form of Sankey diagrams (Fig. 8 and 9) there appeared to be an increase in the consumption of electricity in the experiment where $CO_2$ was captured. To produce 1 MW of electricity (net), in the experiment without capture, the consumption was 133,23 kW, in this case the ASU unit consume the greatest amount of electricity (Fig. 8), while in the experiment with the capture of $CO_2$ it was 199,3 kW for each MW of electricity produced, in this scenario the ASO and acid gas removal and the $CO_2$ capture unit consumed the greatest amount of electricity (Fig. 9).

## 4. CONCLUSIONS

It is necessary to underline that it was the first attempt of material and energy flow analysis in electricity production using UCG gas. The material and energy flow analyzes performed for the technology of electricity production from UCG gas allowed for the following conclusions to be made:

- MEFA enabled the visualization of a material and energy flow between individual unit processes of the technology of electricity production from UCG gas.
- The analysis of material and energy flow networks presented in the form of Sankey diagrams enabled the identification of unit processes with the greatest consumption of raw materials and energy, the greatest emissions to the environment and energy losses.
- The biggest flow of material is connected with the flow of gas extracted during UCG, and electricity production.
- Emissions to the environment from UCG, in the experiment without the capture of $CO_2$ is greater than in the scenario with $CO_2$ capture and is characteristic for the unit process of electricity production where syngas is combusted.
- The experiment without the capture of $CO_2$ to produce 1 MWh of electricity consumes less coal, syngas and electricity than the experiment with the capture of $CO_2$.
- The analyzes performed so far will be used in the next stages of the research to assess the environmental impact of the LCA technique, to analyze the costs of the LCC technique, and to analyze eco-efficiency.
- In subsequent research, based on the data obtained during experiments with the use of the pilot installation within the framework of the project "Development of coal gasification technology for high production of fuels and energy", the following analyses will be conducted: MEFA, MFCA (Material Flow Cost Accounting) and LCA to assess the eco-efficiency of the Underground Coal Gasification process.

## Acknowledgements

This paper is a part of the ongoing Research Task "Development of coal gasification technology for high production of fuels and energy" funded by the National Center for Research and Development under the Strategic Programme for Research and Development titled: "Advanced energy generation technologies". The authors wish to express their gratitude to Prof. Dr. Nikolaus Thißen, Institute for Industrial Ecology INEC, Pforzheim University, Resource Efficiency Management for supporting this paper with comprehensive comments and suggestions.

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