Equivalent Carbon Dioxide Emission in Useful Energy Generation in the Heat-Generating Plant – Application of the Carbon Footprint Methodology

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ABSTRACT

The energy sector worldwide is a significant source of air pollutant emission. In Poland, the vast majority of heat and electricity is generated in coal-fired heat and power plants. There is a common belief that high greenhouse gas emissions from the energy sector in Poland are mainly due to the technological processes involving the conversion of energy by burning fossil fuels. However, coal mining also causes a high environmental burden. This paper aimed to determine the carbon footprint of a typical hard coal-fired heating plant in Poland, taking into account mining of hard coal, its transport to the heating plant and useful energy generation in the heating plant. The investigation carried out allowed comparing the process steps and determining which of them is the dominant source of the greenhouse gas emissions. The obtained results show that hard coal mining and hard coal transport account for almost 65% and 5% of total equivalent carbon dioxide emission, respectively. Energy transformations in the heating plant account for 30% of total equivalent carbon dioxide emission, where approx. 29% is due to hard coal burning and 1% due to electricity consumption. The relative shares of carbon dioxide, methane and nitrous oxide in total equivalent carbon dioxide emission account for approx. 91%, 4% and 5%, respectively.

Keywords: carbon dioxide (CO_2), greenhouse gases (GHG), emission, energy generation, heat plant, coal, carbon footprint (CF)

INTRODUCTION

The carbon footprint (CF) can be used in the analyses on environmental impacts. It is examined in order to quantify the potential influence of the object of study on intensification of the greenhouse effect, and consequently – on climate change. The carbon footprint is the total greenhouse gas (GHG) emissions caused by the object of interest. The procedure for CF calculation corresponds to that used to determine total greenhouse gas emissions in the Life Cycle Assessment (LCA), and can be regarded as a detailed approach to LCA, focused on the "climate change" impact category [BSI 2011].

The greenhouse effect is the process of warming of the Earth's surface and troposphere, as a result of a limited radiation transfer from the Earth's surface and the atmosphere directly into space. The effect is aggravated by the presence of greenhouse gases with polyatomic molecules in the atmosphere. In contrast to the mono- or diatomic gases, the greenhouse gases absorb low frequency radiation emitted by warmed Earth's surface more intensively than high frequency solar radiation. In this way, solar radiation reaches the Earth's surface, while the Earth's radiation is largely absorbed by the atmosphere and re-emitted in all directions, including back to the Earth's surface [Myhre et al. 2013].

The most important gases that directly contribute to the greenhouse effect include [Myhre et al. 2013]:
• water (H_2O),

- carbon dioxide (CO_2),
- methane (CH_4)
- nitrous oxide (N_2O),
- hydrofluorocarbons (HFC),
- perfluorinated compounds:
  - sulfur hexafluoride (SF_6),
  - nitrogen trifluoride (NF_3),
  - perfluorocarbons (PFCs),
- fluorinated ethers (HFE),
- perfluoropolyethers (PFPE),
- chlorofluorocarbons (CFCs),
- hydrochlorofluorocarbons (HCFC).

Water in a gaseous state (water vapor) is the most important for the greenhouse effect and plays an essential role in shaping the Earth's climate. The amount of water vapor in the atmosphere is in direct relation to the temperature. Natural processes, such as ocean, sea and inland water evaporation, as well as plant transpiration, contribute to the water vapor emission to the atmosphere. The anthropogenic sources, such as e.g. evaporation of the water used for irrigation of crops or cooling of power plants, have no significant influence on the greenhouse effect, and consequently – on the global climate. Therefore, water vapor is not included in the inventory of the greenhouse gas emissions associated with human activities.

The methodology for CF calculation includes the assessment of the greenhouse gas emissions all the way through explicit lifetime of the examined object, taking into account direct and indirect emissions, as well as potential emissions, i.e. those avoided due to the existence of the tested object. Each greenhouse gas emission is expressed as equivalent carbon dioxide emission (CO_{2eq}) and the sum of equivalent carbon dioxide emissions values is referred to the functional unit (an element also used in LCA). The carbon footprint is expressed in the emission unit (gram) per the functional unit.

Consistent with the methodology proposed by IPCC [Myhre et al. 2013, IPCC 2006, Houghton et al. 2001], equivalent carbon dioxide emission is obtained by multiplying the emission of a given greenhouse gas by its Global Warming Potential (GWP) for the given time horizon. The GWP value depends on the properties of a greenhouse gas as regards the absorption of electromagnetic radiation and the time period of its remaining in the atmosphere. Usually, GWP refers to the time horizon of 20, 100 or 500 years (the longer the considered period, the greater the error of the GWP value). In many published studies and reports prepared for decision makers, the standard 100-year time horizon is assumed [Myhre et al. 2013]. Regardless the time period used, the GWP value of carbon dioxide is 1, as it is the gas used as the reference. As science and technology advance, new findings are included in IPCC analyses, and consequently, the revised GWP values are presented in subsequent reports. The examples of the GWP values, taken from the Fifth IPCC Report (2013) [Myhre et al. 2013], are presented in Table 1.

CF calculation comprises a complex procedure, which requires defining the boundaries of the system tested, gathering the relevant quantitative data and accurately interpreting the results obtained. Taking an arbitrary decision, as it is done in LCA, can negatively affect the reliability, verifiability and comparability of CF calculations. Even small differences between the methodologies used in calculations can lead to obtaining different CF values for the same study object. This is confirmed by the existing comparative studies, e.g. regarding biofuels [Whittaker et al. 2011] and other products [Dias and Arroja 2012, Garcia and Freire 2014, Pattara et al. 2016, Soode et al. 2013, Wang et al. 2018, Peter et al. 2016], which allow identifying key aspects of the methodology that can lead to the result discrepancies. These include: defining the system boundaries, adopting the cut-off criteria, taking into account (or not)

Table 1. Global warming potentials (GWP) of selected greenhouse gases [Myhre et al. 2013]

Name	Chemical formula	GWP_{20} (20 years horizon)	GWP_{100} (100 years horizon)
Carbon dioxide	CO_2	1	1
Methane	CH_4	84	28
Nitrous oxide	N_2O	264	265
Sulfur hexafluoride	SF_6	17,500	23,500
Carbon tetrachloride	CF_4	4880	6630
Trichlorofluoromethane (CFC-11, freon-11)	CCl_3F	6900	4660

non-fossil carbon dioxide emission, emission allocation rules, and the like [Wang et al. 2018].

The standard methodology for CF calculation was developed and published in the normative documents. The choice of methodology depends on the study object. For a single object, 'Product Carbon Footprint' guidelines are used, and in the case of the whole organization (e.g. an enterprise) – 'Corporate Carbon Footprinting' guidelines. The overall methodology always stays the same; however, detailed assumptions may be different.

The most commonly used international normative documents on the carbon footprint, are:
* 'Publicly Available Specification 2050' (PAS 2050) [2011] – the guidelines developed by the British Standards Institute (BSI) in 2008, revised in 2011;
* 'GHG Protocol Product Standard' [2011] – the guidelines developed by the World Resources Institute (WRI), in cooperation with the World Business Council for Sustainable Development (WBCSD), in 2011;
* ISO 14067. Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification [2018] – the standard developed by the International Organization for Standardization (ISO), based on the existing LCA standards, published in 2013.

PAS 2050 was published first, and then 'GHG Protocol Product Standard' was elaborated based on the methodology developed in PAS 2050. Later, PAS 2050 was revised consistently with 'GHG Protocol Product Standard'. Both documents provide comprehensive guidelines and allow for unambiguous result interpretations. The ISO 14067 carbon footprint standard was published afterwards and is perceived as relatively general; however, some of the provisions of this document are quite precise, e.g. in the case of the guiding principles for quantification of electricity from renewable sources. The basic assumptions of the methodology presented in the three abovementioned documents are the same and based on the existing requirements in the Life Cycle approach, established in the ISO 14040 [2006] and ISO 14044 [2006] standards. Nonetheless, the detailed solutions provided in the aforesaid documents slightly differ from each other, even though the institutions involved in their development (BSI, WRI/WBCSD and ISO) collaborated during preparation/revision of the documents.

In addition to the international initiatives, the actions to develop a consistent methodology for CF calculations have been undertaken at a national or local level, by public or private organizations. The proposed solutions focus on the greenhouse gas emissions alone or include other types of environmental impacts. For instance, the 'Eco-Leaf Environmental Labeling' program has been developed and implemented in Japan [SMPO 2020], and in France, a methodological approach 'French Environmental Footprint BP X30–323' [ADEME 2009] has been developed. Comprehensive evaluation of the approaches used in the normative documents is available in subject literature [Soode et al. 2013, Wang et al. 2018, JRC 2011, Schmied and Knörr 2012].

The use of the methodology for assessing the greenhouse gas emissions in the energy sector has been discussed in several published works. The study [WRI/WBCSD 2006] refers to the methodology recommended in the assessment of the greenhouse gas emissions in energy projects. In [EIB 2020], attention is drawn to the necessity of employing the holistic view to the assessment criteria for the projects in the energy sector, taking into account the economic effect. It is also important to note that the methodology for CF calculations is not as universal as that for LCA.

In the study [De Souza et al. 2018], two methods of electricity supply to the heat pump were compared, i.e. from the national electricity network (the Brazilian electricity mix) and from the solar photovoltaic system. The results obtained showed the prospects to significantly reduce the carbon footprint, in consequence of the use of energy from the photovoltaic system.

Motivating views on the effectiveness of the use of renewable energy in energy projects, based on New Zealand's solutions, were presented in the study [Atkins et al. 2017]. On the other hand, as the authors stated, considerable reduction in the greenhouse gas emissions was in many cases outweighed by high costs of renewable energy.

The study [Aghahosseini et al. 2019] showed the results related to the effectiveness of using renewable energy in the energy sector, in view of the greenhouse gas emissions in the perspective of 2030. Substantial differences in the effectiveness of the use of renewable energy sources were observed, depending on the centralization of the renewable energy supply system.

The greenhouse gas emissions from a coal-fired heating plant were considered in the study

[Gai et al. 2018]. The discussed results indicated that the structures of greenhouse gas emissions might differ notably, depending on the technical solutions applied.

In the study [Agrawal et al. 2014], the Life Cycle approach was used to assess the greenhouse gas emissions and their impacts due to the combined cycle of natural gas and imported coal in a heating plant. IPCC 2001 and Eco-Indicator 99 methods were used for the analysis. Significant ecological benefits were observed due to the use of natural gas. Analogous results were presented in the study [Gonzalez-Salazar et al. 2018], carried out with the aim to compare the effects of hard coal and natural gas utilized in the energy system with the use of different technologies.

This paper aimed to determine the carbon footprint of a typical hard coal-fired heating plant in Poland, taking into account coal mining, coal transport to the heating plant and useful energy generation in the heating plant. The investigation carried out allowed comparing process steps and determining which of them is the dominant source of the greenhouse gas emissions.

METHODOLOGY

The cumulative processes were adopted as the system boundaries in the methodology used for the calculation of equivalent carbon dioxide emission in generation of the useful energy in the coal-fired heating plant:
- hard coal mining – M,
- transport of hard coal to the heating plant – T,
- energy transformations in the heating plant – H.

The considered cumulative processes consist of elementary processes, and are the most important in the functioning of the coal-fired heating plant as regards the greenhouse gas emission.

For the processes examined, the following greenhouse gases were considered:
- hard coal mining: carbon dioxide (CO_2) and methane (CH_4),
- transport of hard coal to the heating plant: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O),
- useful energy generation in the heating plant: carbon dioxide (CO_2).

Annual equivalent carbon dioxide emission (E_{CO2eq}) from the coal-fired heating plant amounts to:

$$E_{CO2eq} = E_{CO2eq-M} + E_{CO2eq-T} + E_{CO2eq-H}, \quad (1)$$

where: $E_{CO2eq-M}$ – equivalent carbon dioxide emission in the process of hard coal mining,

$E_{CO2eq-T}$ – equivalent carbon dioxide emission in the process of hard coal transport f to the heating plant

$E_{CO2eq-H}$ – equivalent carbon dioxide emission in the process of useful energy generation in the heating plant.

Equivalent carbon dioxide emission from each of the processes "X" ($E_{CO2eq-X}$) is the sum:

$$E_{CO2eq-X} = \\ = E_{CO2eq-X-CO2} + E_{CO2eq-X-CH4} + E_{CO2eq-X-N2O}, \quad (2)$$

where: $E_{CO2eq-X-CO2}$ – carbon dioxide emission in the process "X",

$E_{CO2eq-X-CH4}$ – methane emission in the process "X",

$E_{CO2eq-X-N2O}$ – nitrous oxide emission in the process "X".

Equivalent carbon dioxide emission for substance "Y" in the process "X" is:

$$E_{CO2eq-X-Y} = E_{X-Y} \cdot GWP100_Y, \quad (3)$$

where: E_{X-Y} – "Y" substance emission in the process "X",

$GWP100_Y$ – global warming potential of "Y" substance in the 100-year time horizon.

Emission of substance "Y" in the process "X" is calculated as the product:

$$E_{X-Y} = EN_X \cdot WE_{X-Y}, \quad (4)$$

where: EN_X – energy consumption in process "X",

WE_{X-Y} – emission factor for substance "Y" in process "X".

For road transport, emission of substance "Y" can be alternatively calculated as the product:

$$E_{T-Y} = L \cdot b_Y, \quad (5)$$

where: L – the total distance travelled by a means of transport to deliver hard coal to the heating plant,

b_Y – average specific distance emission of substance "Y" from a means of transport of hard coal to the heating plant.

Specific distance emission from road transport of substance "Y" (b_Y) is derived from emission of substance "Y" from road vehicle (m_Y) in relation to distance (s) travelled by this vehicle:

$$b_Y = \frac{dm_Y}{ds} \qquad (6)$$

The most important difficulties in equivalent carbon dioxide emission calculation for the emissions associated with useful energy generation in the coal-fired heating plant, are related to the calculations of:

- emission energy factor for the greenhouse gases in the cumulative processes examined,
- average greenhouse gas specific distance emission from road transport vehicles.

The emission energy factor for the cumulative processes under study was determined based on the emission energy factors calculated for the elementary processes as components of the cumulative processes examined. The average emission of a given greenhouse gas from road transport was expressed by the quotient of the greenhouse gas emission from all road vehicles transporting hard coal to the heating plant and the total distance traveled by these fuels in the transport to heating plants. In practice, calculation of the average emission of specific substances from road transport is most often simplified by using inventory databases for pollutants from road transport, in reference to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [IPCC 2006] and EEA/EMEP Emission Inventory Guidebook 2019 [EEA/EMEP 2019].

CALCULATION RESULTS

The calculation of carbon dioxide equivalent emission was developed for the heating plant that annually used:

- 22.2 Gg of hard coal,
- 6.120 TJ of electricity.

The data on elementary processes were used for the calculation of the carbon dioxide emission energy factor in the process of hard coal mining, consistent with the data on fuel and energy consumption in hard coal mining in 2018, provided by Statistics Poland (formerly: Central Statistical Office, GUS) G-03 [2018] and carbon dioxide emission energy factors developed by KOBiZE [2019] and IPCC guidelines [2006] – Table 2.

The carbon dioxide emission factor in the process of hard coal mining can be calculated in line with the equation below:

$$WE_{M-CO2} = \left(\sum_i WE_{Mi-CO2} \cdot EN_{Mi} \right) \Big/ \sum_i EN_{Mi} \qquad (7)$$

where: WE_{Mi-CO2} – carbon dioxide emission factor in the elementary process "i" in the cumulative process of hard coal mining,
EN_{Mi} – energy consumption in the elementary process "i" in the cumulative process of hard coal mining.

The carbon dioxide emission factor in the hard coal mining process calculated with the use of the equation (7) amounts to 188.82 kg/GJ. The

Table 2. Energy consumption, carbon dioxide emission and energy factor for carbon dioxide emission in the elementary processes of hard coal mining in Poland in 2018

Energy carrier	Energy consumption [GJ]	Carbon dioxide emission [Mg]	Carbon dioxide emission energy factor [kg/GJ]
Liquefied petroleum gas – LPG	287	18	63.10
Lubricating and waste oils, used up	605	44	73.30
Energy efficient hard coal	488 745	46 665	95.48
Coke and semi-coke of coal	422	45	107.00
Diesel oils for combustion engines	464 162	34 394	74.10
Engine and lubricating oils	70 253	5 150	73.30
Petroleum jelly, paraffin waxes, and the like	509	37	73.30
Other kerosene	224	16	73.30
Petroleum spirit and other special spirits	729	53	73.30
Other petroleum products	2 295	168	73.30
Motor gasoline	1 087	75	69.30
Solid biofuels	32 686	0	0.00
Steam and hot water energy	2 086 092	214 867	103.00
Electricity	12 370 860	2 628 808	212.50
Overall	15 518 956	2 930 343	188.82

methane emission factor in the hard coal mining process was assumed 0.331 kg/GJ based on IPCC [2006]. Consistent with KOBiZE [2019], the carbon dioxide emission factor amounted to

212.5 kg/GJ for electricity generation. The parameters assumed for hard coal transport to the heating plant are presented in Table 3.

Table 4 summarizes the data and results from the assessment of carbon dioxide equivalent emission in the production of useful energy in the coal-fired heating plant. The carbon dioxide energy factor values were obtained from the studies carried out by KOBiZE [2017, 2019].

Energy consumption by road transport trucks and average emissions of carbon dioxide, methane

Table 3. Hard coal transport to the heating plant

Parameter	Unit	Value
Distance covered in one trip	km	400
Number of trips	–	888
Truck load capacity	Mg	25

Table 4. Data and results used in the assessment of carbon dioxide equivalent emission in generation of useful energy in a coal-fired heating plant

Assessed processes and factors	Unit	Value
Hard coal consumption in the heating plant	[Gg]	22.2
Consumption of energy from hard coal burned in the heating plant	[TJ]	486.40
Consumption of electricity in the heating plant	[TJ]	6.12
Specific energy consumption in hard coal mining	–	0.00963
Energy consumption in hard coal mining for the heating plant	[TJ]	4.682
Carbon dioxide emission factor in the process of hard coal mining	[kg/GJ]	188.82
Carbon dioxide emission in the process of hard coal mining	[Gg]	91.84
Methane emission factor in the process of hard coal mining	[kg/GJ]	0.4427
Methane emission in the process of hard coal mining	[Gg]	0.2153
Carbon dioxide equivalent emission in the process of hard coal mining	[Gg]	102.62
Carbon dioxide emission factor for coal burned in the heating plant	[kg/GJ]	94.9
Carbon dioxide emission from hard coal burned in a heating plant	[Gg]	46.16
Carbon dioxide equivalent emission from hard coal burned in the heating plant	[Gg]	46.16
Carbon dioxide emission factor for electricity generation for consumption by the heating plant	[kg/GJ]	212.5
Carbon dioxide emission from electricity consumed by the heating plant	[Gg]	1.30
Carbon dioxide equivalent emission from electricity consumed by a heating plant	[Gg]	1.30
Carbon dioxide emission from the heating plant	[GJ]	47.46
Carbon dioxide equivalent emission for the heating plant	[GJ]	47.46
Distance travelled by trucks	[km]	355200
Energy consumption in road transport	[MJ/km]	9.0
Energy consumption in road transport of hard coal to the heating plant	[TJ]	3.192
Specific distance emission of carbon dioxide from road transport of hard coal to the heating plant	[g/km]	584
Carbon dioxide emission from road transport of hard coal to the heating plant	[Gg]	0.2076
Specific distance emission of methane from road transport of hard coal to the heating plant	[g/km]	0.0007
Methane emission from road transport of hard coal to the heating plant	[Gg]	0.00155
Specific distance emission of nitrous oxide from road transport of hard coal to the heating plant	[g/km]	0.0255
Nitrous oxide emission from road transport of hard coal to the heating plant	[Gg]	0.0301
Equivalent carbon dioxide emission from road transport of hard coal to the heating plant	[Gg]	8.2195
Carbon dioxide emission from the process of useful energy generation in the heating plant	[Gg]	144.26
Methane emission from useful energy generation of in the heating plant	[Gg]	0.2169
Nitrous oxide emission from the process of useful energy generation in the heating plant	[Gg]	0.0301
Energy consumption in the process of useful energy generation in the heating plant	[TJ]	500.40
Equivalent carbon dioxide emission in the process of generation of useful energy in the heating plant	[Gg]	158.302
Carbon dioxide emission factor in the process of useful energy generation in the heating plant	[kg/GJ]	288.29
Methane emission factor in the process of useful energy generation in the heating plant	[kg/GJ]	0.4334
Nitrous oxide emission factor in the process of useful energy generation in the heating plant	[kg/GJ]	0.0601
Equivalent carbon dioxide emission factor in the process of useful energy generation in the heating plant	[kg/GJ]	316.353

and nitrous oxide from road transport were calculated based on INFRAS AG software data [INFRAS AG 2010] on traffic conditions equivalent to an average speed of approximately 70 km/h for maximum mass road vehicles (22 ÷ 34) Mg, with defined European emission standard Euro III ÷ Euro VI. Figure 1 shows equivalent carbon dioxide emission from the cumulative processes of useful energy generation in the heating plant. Hard coal mining and hard coal transport account for almost 65% and 5.2% of total equivalent carbon dioxide emission, respectively. Energy transformations in the heating plant account for 30% of total equivalent carbon dioxide emission (29.2% – from hard coal burning and approx. 0.82% from electricity consumption – Figure 2).

In terms of energy transformations in the heating plant, the greenhouse gas emission from hard coal burning is considerably higher when compared to that from electricity consumption. Figures 3–5 depict the carbon dioxide, methane and nitrous oxide emissions from the cumulative processes of useful energy generation of in the heating plant.

Obviously, the highest carbon dioxide emission results, at the outset, from hard coal mining and then from hard coal burning. The methane emission is almost exclusively associated with hard coal mining, whereas nitrous oxide emission is almost exclusively associated with hard coal transport to the heating plant. Figure 6 shows the greenhouse gas emission in the process of useful energy generation in the heating plant and the relevant equivalent carbon dioxide emission values.

The relative shares of methane and nitrous oxide in total equivalent carbon dioxide emission account for 3.84% and 5.03%, respectively. The results of the present study show that in the
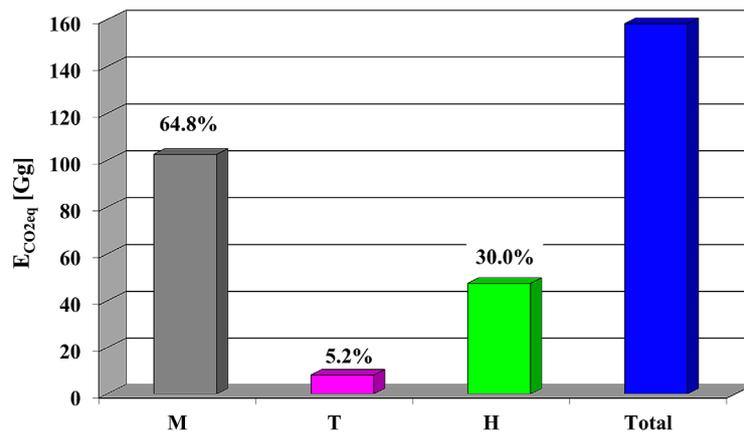

Figure 1. Equivalent carbon dioxide emission from the cumulative processes of useful energy generation in the heating plant: hard coal mining – M, hard coal transport – T, energy transformations in the heating plant – H
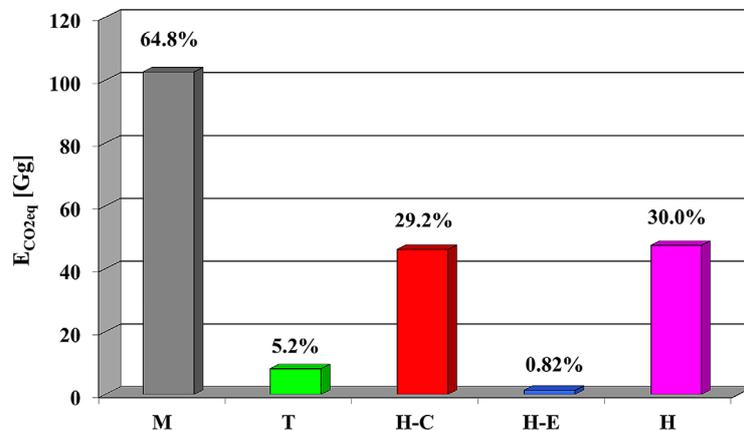

Figure 2. Equivalent carbon dioxide emission from the cumulative processes of useful energy generation in the heating plant: hard coal mining – M, hard coal transport – T, hard coal burning in the heating plant – H-C, electricity consumption in the heating plant – H-E
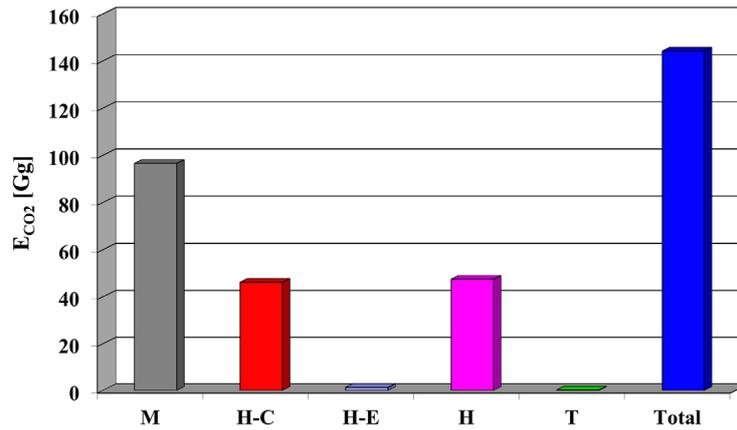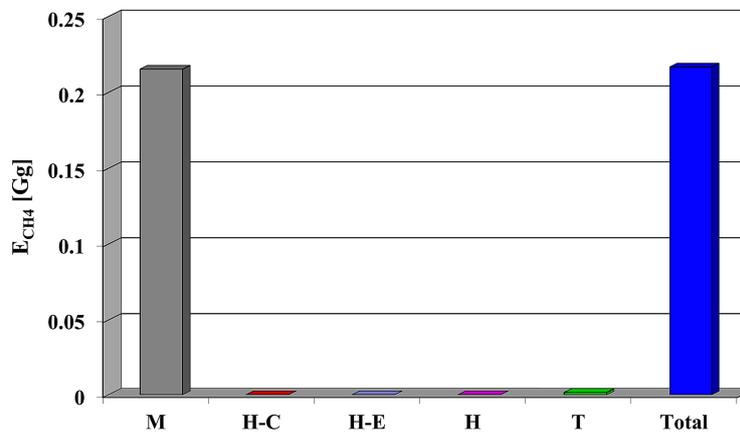
Figure 3. Carbon dioxide emission from the cumulative processes of useful energy generation in the heating plant: hard coal mining – M, hard coal transport – T, hard coal burning in the heating plant – H-C, electricity consumption in the heating plant – H-E

Figure 4. Methane emission from the cumulative processes of useful energy generation in the heating plant: hard coal mining – M, hard coal transport – T, hard coal burning in the heating plant – H-C, electricity consumption in the heating plant – H-E
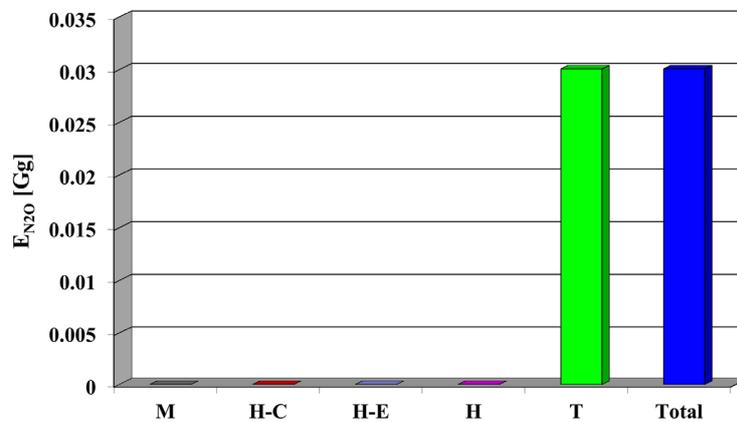

Figure 5. Nitrous oxide emission from the cumulative processes of useful energy generation in the heating plant: hard coal mining – M, hard coal transport – T, hard coal burning in the heating plant – H-C, electricity consumption in the heating plant – H-E
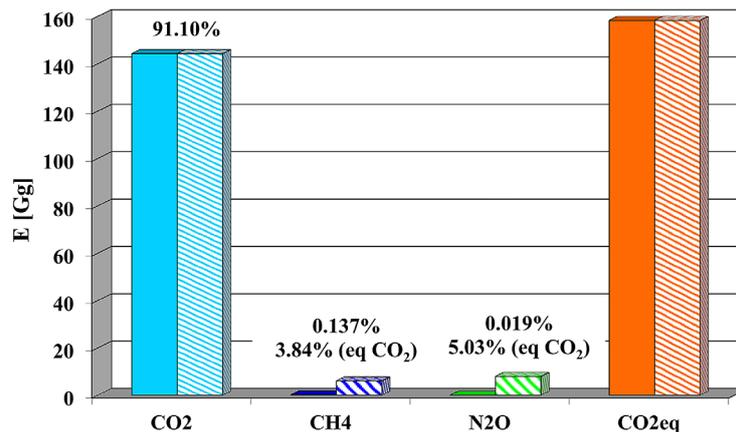
Figure 6. Greenhouse gas emissions in the process of useful energy generation in the heating plant and the relevant equivalent carbon dioxide emission

greenhouse gas emissions from the energy sector, the fossil carbon dioxide emission prevails (over 90%), notwithstanding the relatively low potential of this gas for creating the greenhouse effect when compared to other greenhouse gases.

CONCLUSIONS

The results of the present carbon footprint study, carried out in the selected coal-fired heating plant, indicate that the dominant source of the greenhouse gas emissions is the hard coal mining process. The obtained results contradict with a common belief that burning fossil fuels is generally responsible for high greenhouse gas emissions from the energy sector. It appears that the dominant process in the energy sector is the energy-consuming mining of fossil fuels.

The issue of greenhouse gas emissions is difficult to resolve in the energy sectors of the countries with the economies traditionally based on fossil energy materials/carriers. The solution to this problem has been subject to sustainable development obligations, which equally emphasize the economic, social and ecological aspects. Replacing fossil energy carriers with renewable ones is not always the best solution, not only due to the burden of large investments, but also due to the relatively low power density of such carriers, e.g. wind energy or the energy from photovoltaic systems. The development of nuclear power systems seems to be a good solution. In the latter case, however, there is a risk of problems, which are not only of a financial nature (large capital expenditure), but also result from the social resistance to the nuclear technology.

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