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## Energy-related carbon dioxide emission factors from combustion of gaseous methane fuels

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### Abstract

The topic of this paper concerns energy-related carbon dioxide emission factors from the combustion of gaseous methane fuels. It is a very current subject, as methane fuels, mainly of fossil origin, are one of the primary energy carriers used in industrial and municipal applications for energy purposes. Consequently, the emitted carbon dioxide contributes to the intensification of the greenhouse effect in the atmosphere. The problem of the quantities characterising emissions from the combustion of methane fuels is complicated by the diversity of these fuels. This paper presents background information on the gaseous hydrocarbon fuels and the composition of the main types of natural gas. The structure of natural gas consumption in Poland, depending on the sectors of application for particular types of natural gas, is presented. On the basis of the existing data, aggregated energy-related carbon dioxide emission factors were estimated and analysed. The analysis was carried out for high-methane natural gas (HM), colliery gas (CG) and nitrified natural gas (N)—for the years 1988–2021. Trends in fuel consumption and energy-related carbon dioxide emission factors were determined for the years 1988–2021.

## 1. INTRODUCTION

Gaseous hydrocarbon fuels with a predominantly methane content from natural resources are customarily referred to as natural gas. This is not a precise term, as natural gas is only the raw material for the production of these fuels. A more precise term is gaseous fossil methane fuels.

In addition, the following terms are used:

- depending on the content of the components: high-methane natural gas (HM) for natural gas with a methane content of more than 95% by volume, and nitrified natural gas (N) for natural gas with a nitrogen content of approx. 20% by volume;
- and depending on the source of origin—natural gas from methane drainage of coal mines (i.e., colliery gas (CG)) [WUG 2002–2023] [Kowalik, Gajdowska 2010].

Other non-fossil methane fuels are fuels that are produced from biogas.

Also, gaseous fossil hydrocarbon fuels are those that are produced from refinery gas (petroleum gas, used in liquefied form—LPG) resulting from crude oil processing. Refinery gas is not classified as a methane fuel, the basic components of this gas are propane and butane.

In this article, the term 'natural gas' is used for fuels derived from the processing of natural gas.

As part of the inventory of pollutant emissions from anthropogenic sources, the sectors of civilisational activity

in which natural gas is combusted are also taken into account.

In general, environmental pollution is the occurrence of substances and impacts that are undesirable for the environment, at a rate that makes it possible to alter its properties. In particular, pollution can have harmful effects on the health of humans and other living organisms as well as on the state of the environment. There are different types of pollutants, these may be substances or other types of pollutants, e.g., noise. Usually in the case of air pollution we distinguish:

- substances harmful to the health of living organisms,
- substances promoting the intensification of the greenhouse effect in the atmosphere; the so-called greenhouse gases (GHGs).

For the inventory of GHG emissions, it is necessary to know the emissions of carbon dioxide—the primary GHG from the combustion of natural gas [NIR 2023]. It should be noted that carbon dioxide emissions from the combustion of biogas fuels are not included in the GHG emissions balance, as they are considered renewable fuels.

In general, emissions of each GHG from fuel combustion are based on fuel consumption and the corresponding emission factor. The national GHG emission inventory uses emission factors that denote the ratio of pollutant emissions and the energy equivalent of the combusted fuel.

For the determination of such an energy-related emission factor from the combustion of gaseous fuels, the energy equivalent to the volume of fuel consumed is usually used, thus, fuel consumption data in mass or volume units must first be converted into the energy content of these fuels.

For a mixture in a gaseous fuel of different components with different energy emission factors, the aggregated energy emission factor can be determined based on the following equation:

$$WE_{agr} = \sum_i (u(E/E) \cdot WE_i) \quad (1)$$

where:  $u(E/E)$ —energy content of the  $i$  component,  $WE_i$ —energy-related emission factor of the  $i$  component. The paper presents aggregated energy-related factors of carbon dioxide emissions (hereinafter referred to as the energy carbon dioxide emission factor) from the combustion of natural gas of variable composition in Poland from 1988 to 2021.

The aim of this study is to determine energy factors of carbon dioxide emissions from the combustion of fuels from the processing of natural gas and gas from the demethanation of coal mines. The need to know the energy factors of carbon dioxide emissions from fuel combustion results from formal requirements that are binding for Poland and other countries—parties of the Climate Convention (UNFCCC, United Nations Framework Convention on Climate Change). Poland is obliged to prepare an annual report on GHG emissions covered by the Convention. This report consists of two main documents: the Common Reporting Format (CRF) form and the National Inventory Report (NIR) containing a detailed description on the GHG emission estimation. Together, the two documents form the report and are published on the Convention website.

In order for countries' reports to be a reliable source of data on GHG emissions and to be comparable with one another, as well as consistent throughout the period from the base year (for Poland it is 1988), the Intergovernmental Panel on Climate Change (IPCC) has developed guidelines for performing GHG emission inventories. The IPCC is the body responsible for scientific and methodological matters related to climate change. Poland, like other countries, is obliged to prepare GHG emission inventories in accordance with these guidelines.

Additional sources of knowledge for improving the quality of the GHG emissions reporting include the inventory review reports and recommendations of the experts performing the review.

Both the guidelines and the recommendations from the review of Poland's GHG emission inventories for recent years encourage increasing the level of the quality of emission estimates where possible, with a particular focus on so-called 'key emission sources.' GHG emission inventories should reflect the reality of a country as accurately as possible, therefore expert recommendations for Poland include a gradual transition from default GHG emission factors to a country-specific one. These recommendations

refer mainly to fuel combustion, as this is the main source of emissions in Poland.

In response to these recommendations, the Emission Inventory and Reporting Unit of the National Centre for Emissions Management in the Institute of Environmental Protection, National Research Institute, has undertaken the study of country-specific energy-related emission factors for carbon dioxide emissions from natural gas combustion. This paper includes a review of the literature on the determination of energy-related carbon dioxide emission factors from the combustion of natural gas. The classification of gaseous hydrocarbon fuels and their properties are presented. The factors determining carbon dioxide emissions from the combustion of gaseous hydrocarbon fuels were analysed.

The research was performed for the consumption structure of elementary categories of gaseous hydrocarbon fuels from 1988 to 2021.

The zero-dimensional emission characteristics of natural gas combustion were formalised by introducing the concept of an energy-related emission factor relating to the energy equivalent of the fuel consumed, as different from an emission factor relating to the mass of the fuel used.

Aggregated carbon dioxide emission factors from the combustion of natural gas are then presented.

The paper concludes with a summary of the research results and a list of the cited literature as well as a list of designations.

## 2. LITERATURE REVIEW

There are practically no items in the world literature that consider both the sectors of methane fuels application and the breakdown of these fuels, in terms of pollutant emission characteristics. The IPCC guidelines [IPCC 2006], which are valid for the development of national GHG emission inventories, present methods for estimating emissions according to Tier 1, Tier 2 and Tier 3 methods, which are characterised by increasing detail and representativeness of the IPCC category emission estimates for a given country. The Tier 1 method is fuel-based, since emissions from all sources of combustion can be estimated on the basis of the quantities of fuel combusted (usually from national energy statistics) and average emission factors. In the Tier 2 method for energy, emissions from combustion are estimated from similar fuel statistics, as used in the Tier 1 method, but country-specific emission factors are used in place of the Tier 1 defaults. In the Tier 3 methods for energy, either detailed emission models or measurements and data at the individual plant level are used where appropriate.

In the IPCC guidelines, the default emission factors are available, which can be used if the country does not have developed national emission factors and only if the emission source is not identified as key source. The value of the default carbon dioxide emission factor for natural gas combustion is 56.10 kg/GJ (with the assumed net calorific

value of 48 MJ/kg with the lower and upper limits of the 95% confidence at 46.5 and 50.4 MJ/kg, respectively), regardless of the type of natural gas and its characteristics. However, it is indicated that there is a wide range of values (54.30–58.30 g/MJ) that carbon dioxide emission factors from natural gas combustion can take. EMEP/EEA air pollutant emission inventory guidebook 2019 [EMEP/EEA 2019] describes procedures for determining pollutant emission characteristics for various facilities and for various fuels, sometimes also for various conditions of use of emission sources (as is the case, for example, of road vehicles). In this guide, under the category code NFR (Nomenclature for Reporting) 1.A. (Fuel combustion) in 1.A.1.a subcategory (Public electricity and heat production) three methods are described (Tier 1, Tier 2, and Tier 3). As the method number increases, the detail of the emission estimate increases as well, similarly to the methods indicated in the IPCC guidelines.

The Tier 1 and Tier 2 methods use energy emission factors and the equivalent energy of the fuel consumed during the balancing period. If the pollutant emission estimation for a particular country concerns one year, in that case the averaged pollutant emission is called the national annual pollutant emission.

According to the methodology contained in the guide [EMEP/EEA 2020] [IEA 2020], natural gas types are not distinguished. In this methodology there are no energy-related carbon dioxide emission factors. For the determination of these factors, the method contained in [IPCC 2006] is recommended based on balancing the products of combustion based on the chemical composition of the fuel (assuming completeness of combustion).

The report [IPCC 2007] describes the methodology for determining energy-related GHG emission factors, including carbon dioxide, depending on the types of fuel.

The report [IEA 2022] details the systematics of the use of natural gas in different economic sectors. The International Energy Agency's reporting system for the results of natural gas consumption and its properties is presented, which allows for the determination of emissions.

In report [EPA 2023], the methodology for determining GHG emissions recommended by the Environmental Protection Agency (EPA) is described.

The report [Juhlich 2016] provides an overview of the properties of fossil fuels and energy-related carbon dioxide emission factors under fuel consumption conditions in Germany. For natural gas, energy-related carbon dioxide emission factors are given for fossil natural gas and gas from demethanation of coal mines from 1990 to 2014.

Monograph [Liżewski 2022], in accordance with the Regulation of the Minister of Climate and Environment of 4th July 2022 on the methodology for calculating GHG emissions [Regulation...2022], presents the determination of the emission factors and the calorific value for individual fuels and the energy value of electricity. The methodology pertains to the calculation of energy-related GHG emission factors from fuels other than liquid biofuels and from electricity by entities implementing the National Reduction Goal.

In a presentation [Shermanau 2019], the author presents the basics of the methodology for determining GHG emission factors.

Descriptions of methodologies applied for estimating CO<sub>2</sub> emissions from fuel combustion used by countries reporting GHG emissions under the United Nations Framework Convention on Climate Change are presented in the National Inventory Reports available on the UNFCCC website [UNFCCC 2023].

It is generally not encountered in the literature on the subject to differentiate energy emission factors from the combustion of methane fuels due to the sector of fuel application and the type of fuel.

### 3. RESEARCH METHODOLOGY

The research concerns the following types of natural gas:

- high-methane natural gas (HM)
- gas from demethanation of coal mines (CG)
- nitrified natural gas (N)
- and S as aggregated data.

The economic sectors considered are in line with the emission inventory standards according to the IPCC and EMEP/EEA procedure in points:

#### 1. Energy

##### 1.A. Fuel combustion

Under 1.A., the following sectors of activity are included:

- 1.A.1. Energy industries
- 1.A.2. Manufacturing industries and construction
- 1.A.3. Transport
- 1.A.4. Other sectors, including households, services, and agriculture

The paper considers the energy and industry sectors in a combined manner. Additionally, total activity in all sectors is also considered.

The paper classifies basic categories of natural gas available in Poland and analyses their properties:

- volumetric share of natural gas components of all types,
- calorific value of natural gas of all types.

The research methodology concerns the analysis of factors determining carbon dioxide emissions from natural gas combustion.

The structure of consumption of basic categories of natural gas in Poland in the years 1988– 2021 is analysed. The analysis is performed for the types of fuels and sectors listed in this chapter. Due to the fact that there is a different calorific value of different types of natural gas, the energy equivalent of the consumed fuels is assumed for the assessment of natural gas consumption.

The analysis of aggregated energy carbon dioxide emission factors from the combustion of natural gas in Poland from 1988 to 2021 concerns: high methane natural gas, nitrified natural gas and gas from demethanation of coal mines.

For the analyses contained in the study, the methods described below were used.

On the basis of the results of measurements of gas composition in Poland [GAS-SYSTEM 2023], the average volume shares of the main gas components and their standard deviations were determined. The content of individual components in natural gas, especially methane, determines the carbon content of natural gas and thus the value of energy-related CO<sub>2</sub> emission factors from natural gas combustion. The variability in natural gas composition and especially in methane content confirms that the distinction between gas types in determining the national CO<sub>2</sub> emission factor from natural gas combustion seems justified.

On the basis of multi-year statistical data (1988–2021) [GUS 1989–2022], the analysis of the trend in natural gas consumption by sector and by type of natural gas (HM, N and CG) was carried out. Based on the data concerning CO<sub>2</sub> emission from natural gas combustion coming from the reports of the installations covered by ETS (plant-specific data) [KOBIZE 2022], the aggregated energy-related CO<sub>2</sub> emission factors were calculated for individual years for HM, N and CG. The calculations were carried out for the years 2005–2021, as the ETS data was available for this period. On the basis of the obtained values of aggregated CO<sub>2</sub> emission factors for individual gas types and the consumption structure of individual gas types for the period 1988–2021, country specific aggregated CO<sub>2</sub> emission factors for individual years from the combustion of natural gas in the energy and industry as well other sectors were developed.

The evaluation of the trends of “x” quantities in the time domain is based on formula as follows:

$$B = \frac{k}{AV[x]} \quad (2)$$

where:

B – trend of a physical quantity in the time domain

k – the slope coefficient of a line approximating the set of points describing the relationship between the value of the “x” variable and time

AV[x] – the average value of the “x” quantity

The “x” quantities to which the trend determination method have been applied in this paper are as follows:

- natural gas consumption in the period 1988–2021 for individual sectors,
- energy carbon dioxide emission factor for the years 1988–2021 for individual sectors,
- aggregated energy carbon dioxide emission factor for the years 1988–2021 for individual sectors.

#### 4. ANALYSIS OF THE BASIC CATEGORIES OF NATURAL GAS AND THEIR PROPERTIES

The basic division of natural gas depends on the methane content in natural gas, which is decisively influenced by

the nitrogen content in natural gas. For a high nitrogen content, natural gas is called ‘nitrified,’ for a low content it is called ‘high-methane’ [GUS 2006] [PIG-PIB 2022]. Within the category of nitrified natural gas, a distinction is made between L<sub>s</sub>-type gas with a nitrogen content of 27 % V/V by volume and L<sub>w</sub>-type gas with a nitrogen content of 19.5 % V/V by volume. The higher the nitrogen content in natural gas, the lower its calorific value.

Table 1 provides information on the types of natural gas available in Poland. Application of individual types of natural gas is as follows [PGNiG 2023]:

- high-methane E type gas is found in municipal gas networks and is used in households, businesses and industrial plants;
- nitrified L<sub>s</sub> type gas is supplied only to the local market, to locations close to the gas intake;
- and nitrified L<sub>w</sub> type gas is used in local networks and supplied to households and businesses.

In the case of gases, in determining the composition, it may be assumed that the volume percentage (V/V%) corresponds to the molar percentage (mol %). Molar percentage and percentage by volume should be the same, assuming ideal gas behaviour.

More detailed information on the composition of natural gas in Poland is presented in Table 2 [GAS-SYSTEM 2023]. Relatively low variability of the methane content in natural gas is notable—coefficient of variation for volumetric share of methane in natural gas is approx. 0.06.

The average value for the volumetric share of nitrogen in natural gas is approx. 2.6% and the coefficient of variation is greater than 2, meaning that the variability of values is large.

Volumetric share of ethane in natural gas is low – average value is lower than 2% but variability of the values is significant. Coefficient of variation for volumetric share of ethane in natural gas stands at approx. 0.70.

In the case of propane, the volumetric share in natural gas is practically marginal—the average value is lower than 0.4% and the variability is large, the coefficient of variation is around 0.70.

The volumetric share of carbon dioxide in natural gas is low, with an average value lower than 0.25%, but the variability of the values is high and the coefficient of variation for the carbon dioxide share in natural gas exceeds 1%.

The percentage volume share of oxygen in natural gas is marginal, the average value is lower than 0.003. Variability of values for the volumetric share of oxygen in natural gas—coefficient of variation is higher than 18.

Figure 1 depicts volumetric calorific value of natural gas from sources in Poland [GAS-SYSTEM 2023].

The average value of the volumetric calorific value of natural gas reaches up to 36 MJ/m<sup>3</sup>. The coefficient of variation of the volumetric calorific value of natural gas is just over 0.1. Such a low variability is due to the low content variability of the main natural gas energy component—methane.

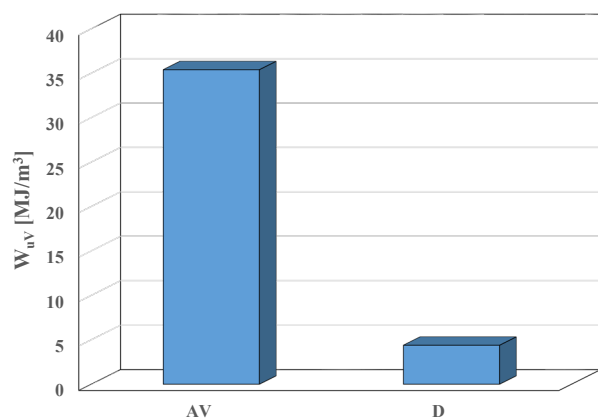
**Table 1.** Types of natural gas [PGNiG 2023]

| Type of natural gas                 |                   | High-methane E type         | Nitrified L <sub>s</sub> type | Nitrified L <sub>w</sub> type |
|-------------------------------------|-------------------|-----------------------------|-------------------------------|-------------------------------|
| Composition                         | Unit              |                             |                               |                               |
| Methane content                     | % V/V             | 97.8                        | 71.0                          | 79.0                          |
| Ethane, propane and butane content  | % V/V             | 1.0                         | 1.0                           | 1.0                           |
| Nitrogen content                    | % V/V             | 1.0                         | 27.0                          | 19.5                          |
| Carbon dioxide and residual content | % V/V             | 0.2                         | 1.0                           | 0.5                           |
| Combustion heat                     | MJ/m <sup>3</sup> | 40.0<br>(no less than 34.0) | 27.9<br>(no less than 26.0)   | 31.0<br>(no less than 30.0)   |

**Table 2.** Percentage share by volume of individual components in natural gas in Poland

| Component      | Percentage content -average value - AV | Standard deviation - D |
|----------------|----------------------------------------|------------------------|
| Methane        | 94.56                                  | 5.874                  |
| Nitrogen       | 2.640                                  | 5.291                  |
| Ethane         | 1.963                                  | 1.356                  |
| Propane        | 0.362                                  | 0.249                  |
| Carbon Dioxide | 0.247                                  | 0.251                  |
| Oxygen         | 0.002                                  | 0.040                  |

Source: Own elaboration based on data from the GAS-SYSTEM database [GAS-SYSTEM 2023]

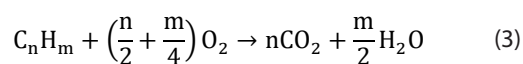
**Figure 1.** Volumetric calorific value— $W_u$  of natural gas in Poland: AV – average value, D – standard deviation

Source: Own elaboration based on data from the GAS-SYSTEM database [GAS-SYSTEM 2023]

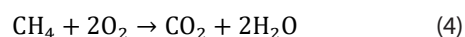
## 5. FACTORS DETERMINING CARBON DIOXIDE EMISSIONS FROM THE COMBUSTION OF NATURAL GAS

Carbon dioxide emissions from the combustion of natural gas are determined by the chemical composition of this fuel. The combustion of natural gas for energy purposes occurs with a high degree of excess air. As a result, in the

flue gas there is a marginal of incomplete combustion products such as carbon monoxide and soot. It can be assumed that the combustion product of the carbon contained in the fuel is only carbon dioxide. Among the products of fuel combustion, nitrogen oxides can also be included, the concentration of which in the flue gas is orders of magnitude lower than that of carbon dioxide. For this reason, natural gas components that do not contain elemental carbon, which can oxidise and form carbon dioxide during natural gas combustion, causing carbon dioxide emissions, are not subject to further analysis. The stoichiometric equation for the combustion of a hydrocarbon fuel (excluding other components contained therein) can be written in the form of:



For natural gas with methane as the dominant hydrocarbon component, the stoichiometric equation of fuel combustion takes the form of:



The calorific value of natural gas depends on its chemical composition. The higher the share of nitrogen and oxygen in the fuel (the share of oxygen is marginal), the lower the calorific value.

Knowing the calorific value of natural gas, it is possible to determine the theoretical value of the carbon dioxide



**Table 3.** Data adopted for high-methane (HM) and nitrified natural gas (N) [PGNiG 2023]

| Parameter  | Unit              | Type of gas |      |
|------------|-------------------|-------------|------|
|            |                   | HM          | N    |
| $W_{um}$   | MJ/kg             | 49.3        | 33.5 |
| $W_{uv}$   | MJ/m <sup>3</sup> | 36.0        | 27.9 |
| $\rho$     | kg/m <sup>3</sup> | 0.73        | 0.83 |
| $u_{CH_4}$ | -                 | 0.98        | 0.79 |

energy factor resulting from the stoichiometric equation of natural gas combustion.

Table 3 shows the data adopted for HM and N;  $W_{um}$  – mass calorific value;  $W_{uv}$  – volumetric calorific value;  $\rho$  – density; and  $u_{CH_4}$  – volume fraction of methane in natural gas corresponding with the mole fraction.

The atomic mass –  $m_a$  (expressed in atomic mass unit – u) for the elements used in the stoichiometric equations of methane oxidation in order to determine the carbon dioxide emission factors are as follows: hydrogen (H) – 1u, carbon (C) – 12u, oxygen (O) – 16u and nitrogen (N) – 14u. For the purposes of the calculations, the concept of apparent molecular mass for a natural gas was introduced ( $m_{mNG}$ ). The apparent molecular weight of a gas mixture is equal to the sum of the products—the mole fraction times the molecular weight of each component [Islam 2022].

Table 4 shows the parameters in the calculation and the results associated with the estimation based on stoichiometric relationships of the carbon dioxide emission factors for HM and N. The following data are presented in Table 4: apparent molecular mass of natural gas –  $m_{mNG}$ ; volume fraction of methane in natural gas corresponding with mole fraction –  $u_{CH_4}$ ; mass of carbon dioxide resulting from the oxidation of methane contained in natural gas –  $m_{CO_2}$ ; carbon dioxide emission factor –  $W_{CO_2}$ ; as well as energy carbon dioxide emission factor –  $WE_{CO_2}$ . The carbon dioxide emission factor –  $W_{CO_2}$  and the energy-related carbon dioxide emission factor –  $WE_{CO_2}$  were determined based on the formulae 5–8.

$$m_{mNG} = \sum_i (u_i \cdot m_{mi}) \quad (5)$$

$$m_{CO_2} = (m_{aC} + 2 \cdot m_{aO}) \cdot u_{CH_4} \quad (6)$$

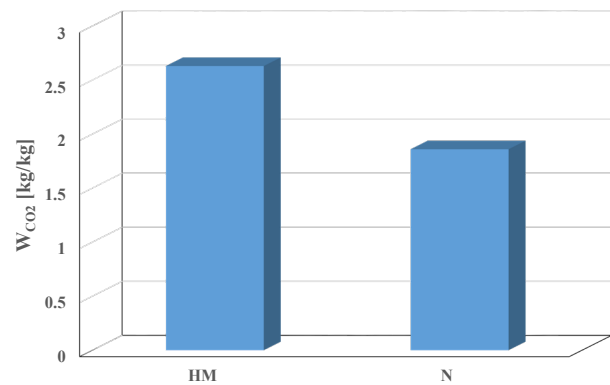
$$W_{CO_2} = \frac{m_{CO_2}}{m_{mNG}} \quad (7)$$

$$WE_{CO_2} = \frac{W_{CO_2}}{W_{um}} \quad (8)$$

Figures 2 and 3 show the carbon dioxide emission factor and the energy carbon dioxide emission factor from the combustion of HM and N.

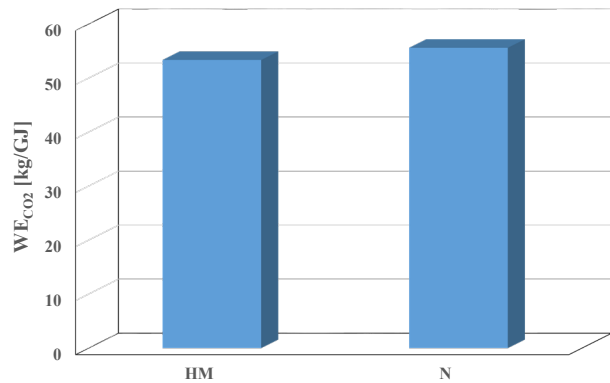
**Table 4.** The data connected with the estimation of the carbon dioxide emission factor –  $W_{CO_2}$  as well as energy carbon dioxide emission factor –  $WE_{CO_2}$  for high-methane (HM) and nitrified natural gas (N)

| Parameter   | Unit  | Type of gas |       |
|-------------|-------|-------------|-------|
|             |       | HM          | N     |
| $m_{mNG}$   | u     | 16.36       | 18.66 |
| $u_{CH_4}$  | -     | 0.98        | 0.79  |
| $m_{CO_2}$  | u     | 43.03       | 34.76 |
| $W_{CO_2}$  | kg/kg | 2.63        | 1.86  |
| $WE_{CO_2}$ | kg/GJ | 53.36       | 55.62 |



**Figure 2.** Carbon dioxide emission factor from combustion of high-methane (HM) and nitrified natural gas (N)

Source: Own elaboration based on data from [PGNiG 2023] and [GAS-SYSTEM 2023]



**Figure 3.** Energy-related carbon dioxide emission factor from combustion of high-methane (HM) and nitrified natural gas (N)

Source: Own elaboration based on data from [PGNiG 2023] and [GAS-SYSTEM 2023]

## 6. STRUCTURE OF CONSUMPTION FOR BASIC CATEGORIES OF NATURAL GAS

Figures 4 to 8 present the structure of natural gas consumption (excluding non-energy use) in Poland during 1988–2021 depending on sectors of application, as expressed in units of energy [GUS 1989–2022] [IEA 2022]. Consumption of natural gas is presented for the following sectors:

- E&I – energy and industries
- T – transport
- O – other sectors, including households, services, and agriculture
- A – all sectors (as aggregation of the E&I, T, and O sectors)

The following methane fuels are considered:

- HM – high-methane natural gas (including CG because in national statistics [GUS 1989–2022] the consumption of CG is included in the consumption of high-methane natural gas)
- CG – gas from demethanation of coal mines (CG)
- HM-CG – high-methane natural gas excluding CG
- N – nitrified natural gas
- S – natural gas of all types (aggregation of HM and N)

By far the highest consumption is in the energy and industry sectors and in the other sectors where households are dominant consumers of natural gas. There is very low natural gas consumption in the transport sector.

This is the trend in natural gas consumption between 1988 and 2021 for the sectors:

- energy and industries: 0.0317,
- transport: 0.0727,
- other sectors, including households, services and agriculture: 0.0183,
- all sectors: 0.0264.

The tendencies in the consumption of HM are similar.

This is the trend in HM consumption between 1988 and 2021 for the sectors:

- energy and industries: 5.57,
- transport: 0.703,
- other sectors, including households, services and agriculture: 3.85,
- all sectors: 10.1.

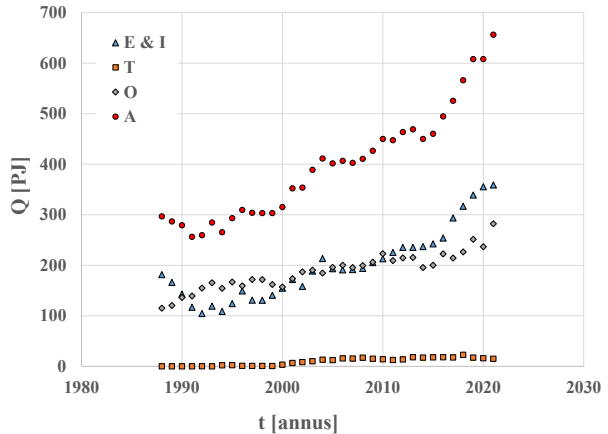
The consumption of CG in the sectors of transportation (T) and the other sectors (O) is practically marginal. The predominant consumption of CG occurs in the energy and industry sectors [Badyda 2008] [Borowski 2018] [Kaliski et al. 2013] [Nawrat et al. 2006].

The trend in consumption of gas from the demethanation of coal mines between 1988 and 2021 is 0.00498 for the sectors of energy and industry (E&I) and all sectors (A).

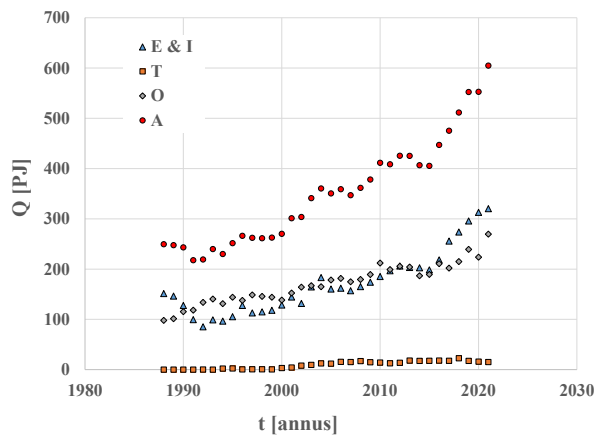
The consumption patterns of HM-CG and HM are similar.

The trend in the consumption of HM-CG from 1988 to 2021 for individual sectors is as follows:

- energy and industries (E&I): 0.0336,
- transport (T): 0.0749,



**Figure 4.** Natural gas consumption (excluding non-energy use) – Q (expressed in energy units) for all types of natural gas (S) in Poland in 1988–2021 by sectors: E&I – energy and industries, T – transport, O – other sectors and A – all sectors



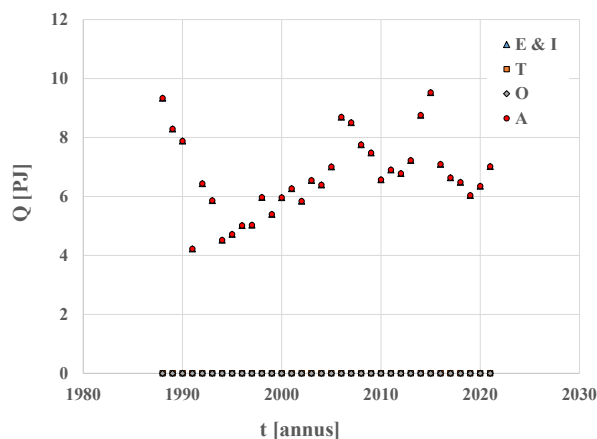
**Figure 5.** High-methane natural gas consumption (excluding non-energy use) – Q (expressed in energy unit) in Poland in 1988–2021 by sectors: E&I – energy and industries, T – transport, O – other sectors and A – all sectors

- other sectors (O), including households, services and agriculture: 0.0225,
- all sectors (as aggregation of E&I, T and O sectors): 0.0293.

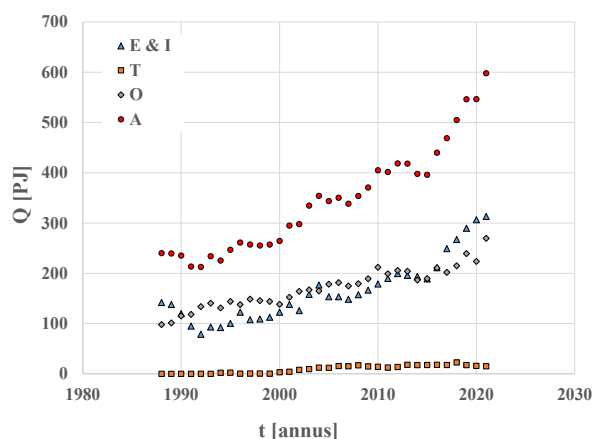
Consumption of N is the highest in the sectors of energy and industries as well as other sectors where households are dominant consumers of N.

This the trend in the consumption of N between 1988 and 2021 for the sectors:

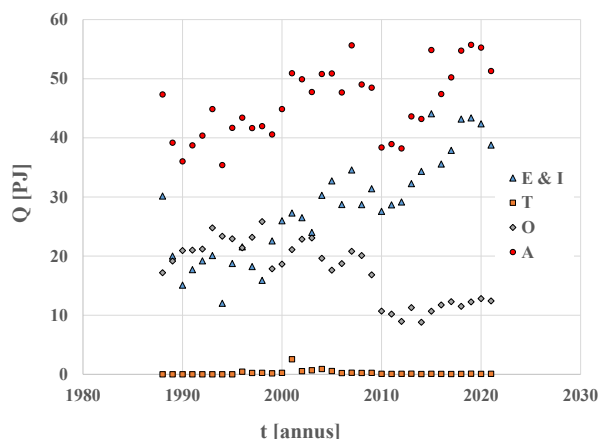
- energy and industries: 0.0269,
- transportation: -0.00827,
- other sectors, including households, services and agriculture: -0.0231,
- all sectors (as aggregation of E&I, T and O sectors): 0.00770.



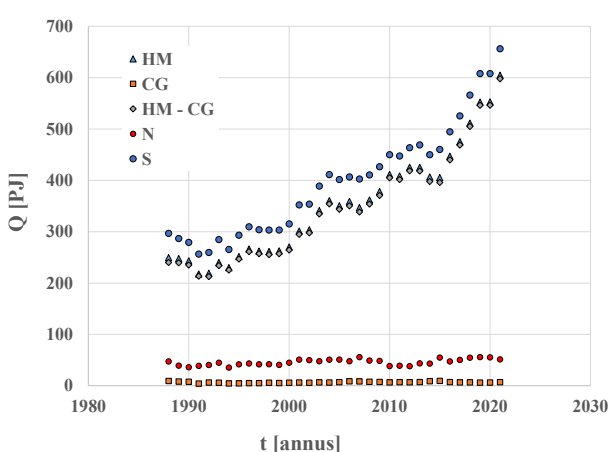
**Figure 6.** Colliery gas consumption (excluding non-energy use) – Q (expressed in energy unit) in Poland in 1988–2021 by sectors: E&I – energy and industries, T – transport, O – other sectors, and A – all sectors



**Figure 7.** HM excluding CG consumption (excluding non-energy use) – Q (expressed in energy units) in Poland in 1988–2021 by sectors: E&I – energy and industries, T – transport, O – other sectors, and A – all sectors



**Figure 8.** Nitrified natural gas consumption (excluding non-energy use) – Q (expressed in energy units) in Poland in 1988–2021 by sectors: E&I – energy and industries, T – transport, O – other sectors, and A – all sectors



**Figure 9.** Natural gas consumption (excluding non-energy use) – Q (expressed in energy units) for all sectors of application (A) in Poland in 1988–2021 by types of natural gas: HM, CG, HM-CG, N, and S

It is noticeable that in the transport sector there is a negative trend in the consumption of N, which is related to the fact that N has a lower calorific value than HM, and there is a preference for using fuels with a high calorific value to power internal combustion engines.

Figures 9–12 show the structure of natural gas consumption excluding non-energy use in Poland from 1988 to 2021 by application sector and type of natural gas, expressed in units of energy [GUS 1989–2022] [IEA 2022].

This the trend of natural gas consumption for all sectors of application from 1988 to 2021 depending on fuel types:

- HM: 0.0287,
- CG: 0.00498,
- HM-CG: 0.0293,
- N: 0.00770,
- S: 0.0264.

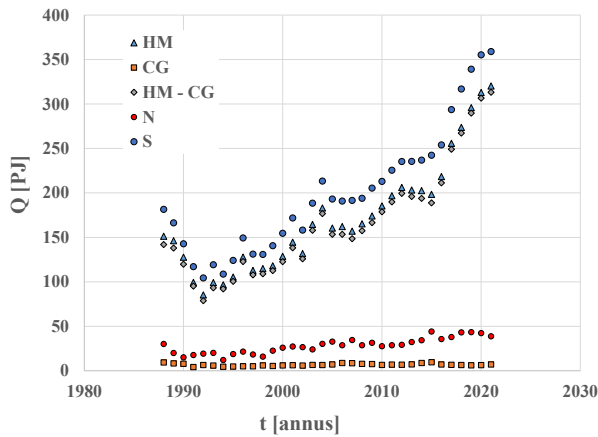
This the trend of natural gas consumption for the sectors of energy and industry from 1988 to 2021 depending on fuel types:

- HM: 0.0325,
- CG: 0.00498,
- HM-CG: 0.0336,
- N: 0.0269,
- S: 0.0317.

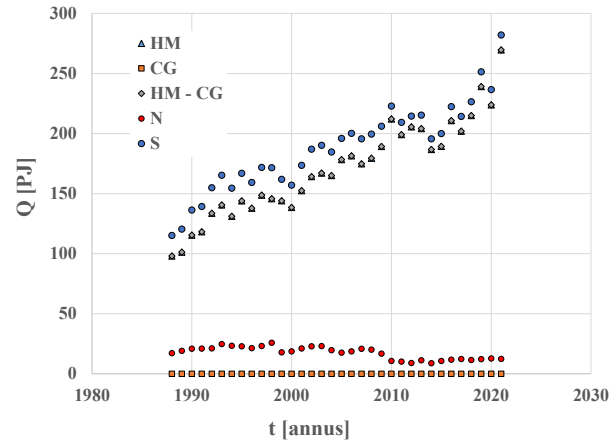
This the trend of natural gas consumption for the sector of transport from 1988 to 2021 depending on fuel types:

- HM: 0.0749,
- HM-CG: 0.0749,
- N: -0.00830,
- S: 0.0727.

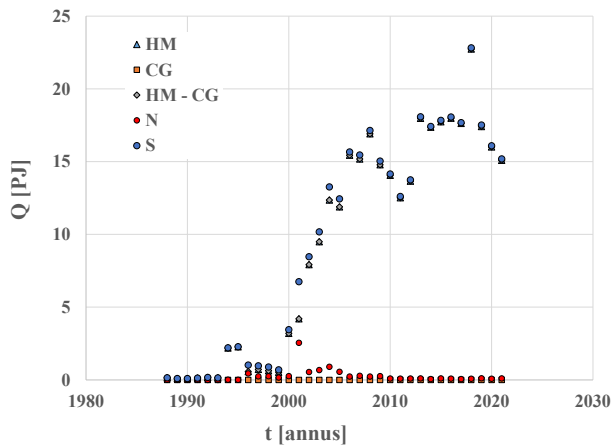




**Figure 10.** Natural gas consumption (excluding non-energy use) – Q (expressed in energy unit) for energy and industry sectors (E&I) in Poland in 1988–2021 by types of natural gas: HM, CG, HM-CG, N, and S



**Figure 12.** Natural gas consumption (excluding non-energy use) – Q (expressed in energy units) for other sectors (O) in Poland in 1988–2021 by types of natural gas: HM, HM-CG, N, and S



**Figure 11.** Natural gas consumption (excluding non-energy use) – Q (expressed in energy units) for transport sector (T) in Poland in 1988–2021 by types of natural gas: HM, HM-CG, N, and S

In the case of CG, there was no consumption in the transport sector during the analysed period.

This the trend of natural gas consumption for the other sectors including households, services, and agriculture from 1988 to 2021 depending on fuel types:

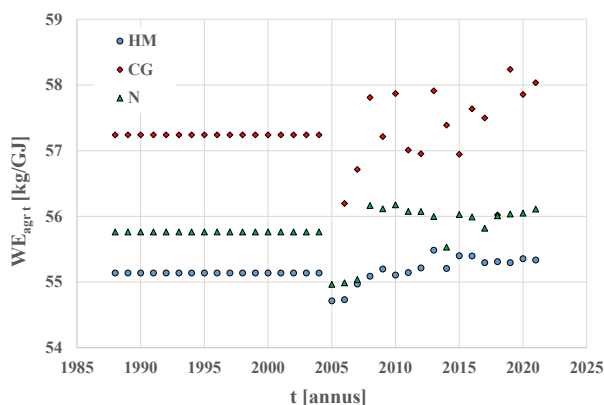
- HM: 0.0225,
- HM-CG: 0.0225,
- N: -0.0231,
- S: 0.0183.

In this group, the consumption of CG occurred incidentally and was not significant.

## 7. THE ANALYSIS OF AGGREGATED ENERGY CARBON DIOXIDE EMISSION FACTORS FROM THE COMBUSTION OF NATURAL GAS

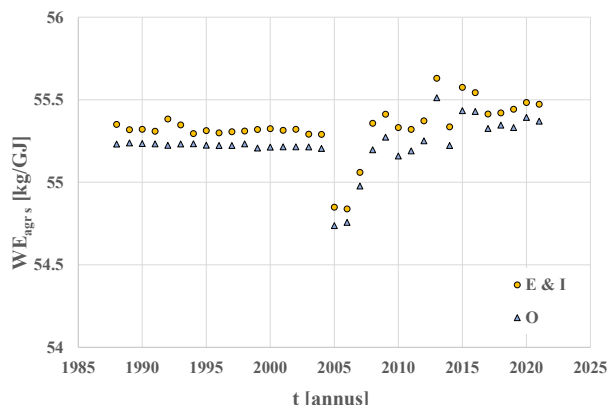
The value of the aggregated energy carbon dioxide emission factor was determined on the basis of plant-specific energy-related factors of carbon dioxide from the EU ETS (European Union Emissions Trading System) database [KOBIZE 2022] and the structure of consumption of individual types of natural gas [GUS 1989–2022].

Figure 13 shows the aggregated energy factor of carbon dioxide emissions for total natural gas consumption in Poland from 1988 to 2021—for HM, CG and N. For the years 1988–2004, the aggregated energy carbon dioxide emission factor was taken as the arithmetic mean of the values of the aggregated carbon dioxide emission factor for the years 2005–2016. It is due to the lack of data from EU ETS reports to estimate the CO<sub>2</sub> country-specific emission factor for historical years before 2005 (it is the year of the first submission of the reports under EU ETS regulations). For HM, the linear trend of the energy carbon dioxide emission factor from 1988 to 2021 is increasing very slightly—the slope of the line approximating the set of points is only 0.0008. This coefficient for N is 0.0091, while for CG it is equal to 0.0067. The values of the energy carbon dioxide emission factors— $WE_{agr\ t}$ —estimated based on data from EU ETS reports fell within the following ranges for the analysed period for particular types of natural gas: HM 54.71–55.49 kg/GJ, N 55.76–56.11 kg/GJ, and CG 56.02–58.23 kg/GJ. Detailed data for particular types of natural gas in the years 2005–2021, for which estimation was based on the plant-specific data reported under EU ETS regulations, is presented in Table 5. The greatest variability in the values of the carbon dioxide emission factor is found in CG, which is due to its varying composition.



**Figure 13.** Aggregated energy carbon dioxide emission factors— $WE_{agrt}$ —for particular types of natural gas (HM, CG, and N) in Poland in 1988–2021 estimated on the basis of the plant-specific data reported under ETS. The values for 1988–2004 are the arithmetic means of the values for the years 2005–2016

Source: Own elaboration based on data from [KOBiZE 2022]



**Figure 14.** Aggregated energy carbon dioxide emission factors— $WE_{agrs}$ —for natural gas combustion in the sectors of energy and industry (E&I) as well as other sectors (O) in Poland in 1988–2021

Source: Own elaboration based on data from [KOBiZE 2022] [GUS 1988–2022] [IEA 2022]

**Table 5.** Aggregated energy carbon dioxide emission factors— $WE_{agrt}$  [kg/GJ]—for individual types of natural gas in Poland in 2005–2021

| Type of natural gas      | 2005  | 2006  | 2007  | 2008  | 2009  | 2010  | 2011  | 2012  | 2013  |
|--------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| High-methane natural gas | 54.71 | 54.73 | 54.97 | 55.09 | 55.20 | 55.11 | 55.14 | 55.22 | 55.49 |
| Nitrified natural gas    | 54.97 | 54.99 | 55.04 | 56.17 | 56.12 | 56.18 | 56.08 | 56.07 | 56.00 |
| Colliery gas             | 57.24 | 56.20 | 56.72 | 57.81 | 57.21 | 57.87 | 57.01 | 56.95 | 57.91 |
| Type of natural gas      | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  |       |
| High-methane natural gas | 55.21 | 55.40 | 55.40 | 55.30 | 55.31 | 55.30 | 55.36 | 55.34 |       |
| Nitrified natural gas    | 55.53 | 56.03 | 55.99 | 55.82 | 56.01 | 56.04 | 56.05 | 56.11 |       |
| Colliery gas             | 57.39 | 56.94 | 57.64 | 57.50 | 56.02 | 58.24 | 57.86 | 58.03 |       |

Source: Own elaboration based on data from [KOBiZE 2022]

Figure 14 shows the aggregated energy carbon dioxide emission factors for natural gas combustion in the energy and industry sectors (E&I) and other sectors (O) including households, services and agriculture in Poland from 1988 to 2021. These values were estimated based on the aggregated carbon dioxide emission factors for individual types of natural gas ( $WE_{agrt}$ ) presented in the Table 5 and the structure of energy consumption of natural gas described earlier in this article and presented in Figures 4–12.

Until 2004, the variability of the aggregated energy carbon dioxide emission factor is low. This is due to unavailability of plant-specific carbon dioxide emission factors from EU ETS reports.

The linear trend of the energy carbon dioxide emission factor from 1988 to 2021 is similar for the sectors of energy and industry as well as other sectors—the slope of the line approximating the set of points is 0.0049 and

0.0043, respectively. The values of the energy carbon dioxide emission factors— $WE_{agrs}$ —in the analysed period amounted to the range of 54.84–55.63 kg/GJ for energy and industry (E&I), and 54.74–55.51 kg/GJ for the other sectors (O).

Table 6 presents individual values of aggregated energy-related carbon dioxide emission factors in the energy and industry (E&I) and the other sectors (O) for the years 2005–2021, for which the estimation was made on the basis of available plant-specific data allowing the determination of emission factors for each type of natural gas for a given year (Table 5).

Prior to 2005, the fluctuations in the values of the energy-related carbon dioxide emission factors ( $WE_{agrs}$ ) in the sectors analysed are very small and are only determined by the changes in the consumption structure of the different types of natural gas. The reason for this is the described

**Table 6.** Aggregated energy carbon dioxide emission factors— $WE_{agr}$  [kg/GJ] —for natural gas combustion in the sectors of energy and industry (E&I) as well as other sectors (O) in Poland in 2005–2021

| Sectors                   | 2005        | 2006        | 2007        | 2008        | 2009        | 2010        | 2011        | 2012        | 2013  |
|---------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------|
| Energy and industry (E&I) | 54.85       | 54.84       | 55.06       | 55.36       | 55.41       | 55.33       | 55.32       | 55.37       | 55.63 |
| Other sectors (O)         | 54.74       | 54.76       | 54.98       | 55.20       | 55.27       | 55.16       | 55.19       | 55.25       | 55.51 |
| Sectors                   | <b>2014</b> | <b>2015</b> | <b>2016</b> | <b>2017</b> | <b>2018</b> | <b>2019</b> | <b>2020</b> | <b>2021</b> |       |
| Energy and industry (E&I) | 55.34       | 55.58       | 55.54       | 55.41       | 55.42       | 55.44       | 55.48       | 55.47       |       |
| Other sectors (O)         | 55.22       | 55.43       | 55.43       | 55.33       | 55.35       | 55.33       | 55.39       | 55.37       |       |

Source: Own elaboration based on data from [KOBiZE 2022] [GUS 1988-2022] [IEA 2022]

lack of data and the therefore assumed constant values of carbon dioxide emission factors ( $WE_{agr}$ ) for individual gas types from 1988 to 2004. The values of the estimated country specific emission factors ( $WE_{agr}$ ) for all years are lower than the default indicator of carbon dioxide emissions from natural gas combustion recommended in the IPCC guidelines (56.10 kg/GJ).

## 8. CONCLUSIONS

In summary of the considerations presented in this paper, the following conclusions can be drawn:

1. Methane fuels include fuels produced from:
  - fossil raw material–natural gas,
  - demethanation of coal mines,
  - and biological sources.

The first two of these fuel types contribute to intensification of the greenhouse effect, unlike fuels of biological origin i.e. renewable fuels. Methane fuels produced from natural gas are additionally classified according to nitrogen content as: high-methane and nitrified. In general, methane fuels produced from fossil raw material and from the demethanation of coal mines are referred to as natural gas.

2. In the emission of gases contributing to the intensification of the greenhouse effect in the atmosphere (resulting from the combustion of non-renewable methane fuels), carbon dioxide is predominant. For the determination of pollutant emissions from fuel combustion, it is necessary to know the emission characteristics and consumption of the fuels. Due to the combustion of various fuels, it is justified to use energy-related pollutant emission factors and the equivalent energy of the fuels consumed. The pollutant emission energy factor is the ratio of the pollutant emission amount and the fuel-equivalent energy consumed, which is derived from quantity of fuel use and that calorific value. The aggregated pollutant energy factor is a linear correlation of the energy emission factors of particular pollutants and the energy equivalent of the consumption of that.

3. The following fuel types are considered in balancing natural gas consumption:

- high-methane natural gas,
- colliery gas,
- nitrified natural gas.

Various types of fuels, classified as natural gas, differ considerably in their chemical composition and properties, in particular in their calorific value.

The following sectors are considered in the analysis:

- energy and industry,
- transportation,
- other sectors, including households, services and agriculture,
- and all sectors, as aggregate information.

The consumption of the various fuel types in the different sectors varies greatly. Consumption trends of the various fuel types in the different sectors also vary.

4. An analysis of aggregate energy carbon dioxide emission factors developed based on ETS report data and the structure of natural gas consumption indicate that the annual development of national indicators should continue, as different values are obtained each year. The values estimated so far for each year turned out lower than the default carbon dioxide factor recommended by the IPCC. The use of country specific emission factors allows for a more accurate estimation of national annual GHG emissions (e.g., avoiding overestimation of emissions in the national GHG inventory). In addition, the development of the national methodology for GHG emission estimation is in line with IPCC recommendations, especially for the major fuels in the national energy balance.

5. As data becomes available, supplementation of historical data prior to 2004 may also be considered in estimating the value of the energy carbon dioxide emission factor from natural gas combustion for an individual year.

6. It is appropriate to continue research into the determination of emission factors for pollutants other than carbon dioxide—not only GHGs, but also substances harmful to the health of living organisms.

## LIST OF DESIGNATIONS

A – natural gas for all applications  
AV – average value  
B – trend of a physical quantity in the time domain  
 $C_2H_6$  – ethane  
 $C_3H_8$  – propane  
CG – gas from demethanation of coal mines (colliery gas)  
 $CH_4$  – methane  
D – standard deviation  
E – energy  
E & I – energy and industries  
EEA – European Environment Agency  
EMEP – Environmental Monitoring and Evaluation Programme  
EU ETS – European Union Emissions Trading System  
GHG – Greenhouse gases  
HM – CG – high-methane natural gas excluding gas from the demethanation of coal mines  
HM – high-methane natural gas  
IEA – International Energy Agency  
k – slope of a line approximating the set of values in time domains  
LPG – liquefied petroleum gas

Ls – type of nitrified natural gas  
Lw – type of nitrified natural gas  
 $m_a$  – atomic mass  
 $m_m$  – molecular mass  
N – nitrified natural gas  
 $N_2$  – nitrogen  
O – other sectors, including households, services, and agriculture  
Q – energy equivalent of fuel consumed  
 $\rho$  – density  
S – natural gas of all types  
t – time  
T – transport  
u – unified atomic mass unit  
 $u_i$  – volume fraction of component “i” in the mixture  
UNFCCC – United Nations Framework Convention on Climate Change  
WE – energy-related factor of pollutants emission  
 $WE_{agr\ t}$  – energy-related  $CO_2$  emission factor aggregated by type of natural gas  
 $WE_{agr\ s}$  – energy-related  $CO_2$  emission factor aggregated by sector  
 $W_{um}$  – mass calorific value  
 $W_{uv}$  – volumetric calorific value

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