Carbon Footprint of Electricity Production

A methodology for calculating the carbon footprint of electricity production has been developed, which meets the requirements of the ISO 14067 standard and the methods of inventorying greenhouse gas emissions of the Intergovernmental Panel on Climate Change. Calculations of the carbon footprint of electricity production using hard coal and natural gas, as well as its components, were performed for all stages of electricity production: during the construction of power plants, fuel extraction and fuel transportation, production and transportation of electricity, and waste management of its production. A comparison of the calculation results with literature data showed a significant excess of the carbon footprint of electricity production, which is produced using hard coal and natural gas at power stations in Ukraine. The reasons for exceeding the carbon footprint of electricity production in Ukraine relative to values in other countries are explained. It was determined that the reasons for such an excess are not only due to different levels of technical condition of power plant equipment, but also depend on calculation methods, in particular, the use of different limits of the life cycle of electricity production. Also (in the case of using natural gas) using different methods of distribution of fuel costs for the production of heat and electricity in the case of combined production of heat and electricity. Expected that the results of the work will be used in the calculations of the products carbon footprint for which uses electricity. Bibl. 18, Tab. 5.

Keywords: greenhouse gases, carbon footprint of electricity production, specific fuel consumption, coal, natural gas.

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Reduction of greenhouse gas (GHG) emissions is one of the most urgent problems in the development of the world economy, which the international community is trying to solve already at the level of legislation of both individual countries and interstate entities. Thus, the EU countries, for example, recently adopted a package of important documents [1], which is particularly significant for Ukraine, given its European integration aspirations. This determines the importance of adequately defining such an indicator of the efficiency of economic activity as the carbon footprint of products and, in particular, the carbon footprint of electricity used in all spheres of human activity. The importance of using the carbon footprint tool is emphasized by its significance for the functioning of the system of economic levers aimed at ensuring sustainable development [2].

The carbon footprint of electricity [3] includes GHG emissions:

- during production and transportation of fuel or biomass cultivation;
- in the production of electricity (taking into account losses during the transmission and distribution of electricity);
- at the final stage of the life cycle of electricity (for example, handling waste that occurs when using nuclear fuel or slag from thermal power plants).

According to [3], the carbon footprint of products is the sum of emissions and removal of all types of GHG in the production system, which is expressed in the equivalent of weight units of carbon dioxide (CO₂-eq.) and is calculated based on the assessment of the life cycle of products. The life cycle of a product (ISO 14067:2018(E)) is the successive and interconnected stages associated with a product from the acquisition of raw materials or its manufacture from natural resources to final disposal at the end of its useful life. The concept of the product life cycle also includes the construction stage. In this case, it may be about GHG emissions during the creation of the main production assets for the extraction of raw materials and materials necessary for the production of electricity, as well as power plants themselves. This component of the carbon footprint must be taken into account to ensure the comparability of different sources of electricity because for renewable energy sources this component may exceed the rest of the components of the carbon footprint of electricity production (CFEP). The requirement to ensure comparability and transparency is put forward to international reporting at almost all levels and it is declared among the key requirements for the preparation of materials in the documents of the UN Framework Convention on Climate Change [4].

As you know, GHG emissions do not occur directly during the transmission and distribution of electricity. These losses simply lead to an increase in its production to cover the electricity losses. Therefore, GHG emissions caused by electricity losses should be considered not as an addition, but as a multiplier to the sum of all components of the carbon footprint of electricity.

In this article, a methodology for calculating all components of the CFEP without taking into account losses during transmission and distribution of electricity is proposed. Therefore, this publication uses the term GHG rather than the carbon footprint of electricity to emphasize that it is the carbon footprint of electricity at the busbars of power plants.

The largest GHG emissions in the production of electricity in Ukraine are due to the burning of carbon-containing fuels — hard coal and natural gas. The use of renewable energy sources for electricity production is practically carbon neutral. The volumes of electricity produced using renewable energy sources (RES) are relatively small (in 2020 they accounted for 12.4% of the total volumes of electricity production [5]). Moreover, power plants that use RES have a small capacity. It should also be noted that the majority of electricity produced using renewable energy sources, except for electricity produced at hydroelectric power stations, is produced by households for their own needs. Therefore, it can be assumed that electricity produced using RES is not used in the extraction and production of fuel.

In addition to burning carbon fuels, electricity is produced using nuclear fuel, which consumes electricity and carbon fuels. Therefore, the production of electricity at nuclear power plants (NPPs) cannot be considered carbon neutral. The amount of CFEP produced at the NPP is estimated [6, 7] to be within 3.7–110 kg CO₂-eq./MWh. In the CFEP calculation process the components due to the use of hard coal and natural gas, as well as the CFEP produced at the NPP, which is determined [8] at the level of 117 kg CO₂-eq./MWh, were taken into account.

The developed methodology can be used to calculate CFEP produced using other types of fuel,
for example, synthetic natural gas [9], hydrogen and atomic-hydrogen fuel [10], as well as in the comprehensive consideration of the technical and economic aspects of the reconstruction of Ukrainian thermal power plants in conditions of rising costs of greenhouse gas emissions [11]. It is expected that the work results will be used in the calculations of the carbon footprint of products, the production of which uses electricity. The products carbon footprint is used as an economic lever to reduce GHG emissions. After ensuring compliance of its quantity value with internationally established parameters, access to international, including European, commodity markets is opened for national producers. In addition, the use of information about the carbon footprint in product labeling significantly increases the demand for products with lower carbon footprint among similar types of products.

Calculation of the Carbon Footprint of Electricity Production

In accordance with the requirements of [1], the value of the SFEP can be calculated using the formula:

$$ c_s = c_s^c + c_s^e + c_s^t + c_s^p + c_s^r, \quad (1) $$

where $s$ — index of the type of fuel from which electricity is produced; $c_s$ — is the amount of CFEP, kg CO$_2$-eq./MWh; components of the CFEP from fuel of the $s$-th type, due, respectively: $c_s^c$ — to the construction of power plants, kg CO$_2$-eq./MWh; $c_s^e$ — fuel extraction and production, kg CO$_2$-eq./MWh; $c_s^t$ — fuel transportation, kg CO$_2$-eq./MWh; $c_s^p$ — GHG emissions that occur during the production, transmission and distribution of electricity, kg CO$_2$-eq./MWh; $c_s^r$ — by GHG emissions during the handling of electricity production waste, kg CO$_2$-eq./MWh.

GHG emissions, which occur at various stages of electricity production, can be due to two main reasons — GHG leakage (in the process of fuel extraction, transportation or distribution) and fuel combustion.

In general, the components of GHG caused by GHG leakage in the process of fuel extraction, transportation or distribution can be calculated using the formula:

$$ c_s^f = \frac{b_v}{k_v^f} \sum u \lambda_{uv} \sum v a_{vuv} p_v 10^3, \quad (2) $$

where $u$ — index of the country in which the fuel is produced; $v$ — index of type of GHG; $b_v$ — specific consumption of the fuel type for electricity production, tce./MWh; $k_v^f$ — coefficient of conversion of fuel production volumes of the $s$-th type in natural units of measurement in a unit of conventional fuel, tce./n.u. $s$-th type of fuel; $\lambda_{uv}$ — share of the $s$-th type of used imported fuel from the $u$-th country, relative units, r.u.; $a_{vuv}$ — specific emissions of the $v$-th type of GHG when displaying the $s$-th type of fuel in the $u$-th country, t CO$_2$-eq./t of the $v$-th type of GHG.

Carbon dioxide ($v = 1$), methane ($v = 2$) and nitrous oxide ($v = 3$) emissions occur during electricity production. In accordance with the requirements adopted by the UNFCCC for the preparation of reports, the global warming potential is assumed to be equal to: for carbon dioxide (CO$_2$) — 1, for methane (CH$_4$) — 25, and for nitrous oxide (N$_2$O) — 298. The specific coal and natural gas consumption for electricity production were taken according to information of JSC “Ukrenergo” on the operation of the energy complex for 12 months of 2017 for thermal power plants and combined heat and power plant. The specific consumption of nuclear fuel was determined based on the data of the energy balance of Ukraine.

The largest GHG emissions in the production of electricity occur during the burning of hard coal and natural gas. It is proposed to use the fuel type index $s = 1$ for hard coal, and $s = 2$ for natural gas. The use of other types of fuel leads to significantly lower GHG emissions. Therefore, their indexing can be used depending on the types of fuel, for which the ESA is determined.

Natural units of measurement of fuel are used in the work: tons for hard coal, thousand m$^3$ for natural gas.

For Ukraine, the index $u$ is taken equal to 1.

The components of GHG due to fuel combustion can be calculated using the formula:

$$ c_s^c = \frac{b_v}{k_v} \sum u \sum q \lambda_{qu} a_{quv} \sum v k_{quv} p_v 10^3, \quad (3) $$

where $q$ — the index of the type of fuel or energy resource used for fuel production; $\lambda_{qu}$ — the share of the $q$-th type of fuel, which is imported from the $u$-th country, directly; $a_{quv}$ — specific consumption of the $q$-th type of fuel during extraction and
production of the s-th type of fuel in the u-th country, n.u. q-th type of fuel/n.u. s-th type of fuel; $k_{quv}^C$ — coefficient of GHG emissions when burning the q-th type of fuel, which is imported from the u-th country or produced in Ukraine (u = 1), t/n.u. q-th type of fuel.

The indexing order for the types of fuel used for fuel production is the same as for the main fuel: $q = 1$ for hard coal, $q = 2$ for natural gas, and $q = 3$ for nuclear fuel.

In the absence of the necessary data (for example, when calculating the components of CFEP in the construction of power plants or at the final stage of the life cycle of electricity production), proportional ratios between known and unknown values CFEP can be used to estimate the value of CFEP components. As a rule, these components of CFEP are insignificant, compared to the main component of CFEP, which is due to the burning of fuel during the production of electricity.)

### Construction of Power Plants

To estimate the carbon footprint of power plant construction, you can use the data [8] on the carbon footprint of NPP construction, which was estimated as 23.3 kg CO$_2$-eq./MWh. At the same time, the carbon footprint of TPP and CHP construction can be determined by the ratio of the cost of power plant construction. These ratios in different countries are in a wide range. In the Table 1 shows data on the average ratio of the cost of power plant construction, determined according to indicators [4], and estimates of the component of the CFE caused by the construction of power plants of different types, assuming the same time of operation of power plants.

### Table 1. Capital costs and assessment of the component of the carbon footprint of electricity caused by the construction of a power plant

<table>
<thead>
<tr>
<th>The name of the value</th>
<th>Power plant type</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of power plant construction, $$/kW</td>
<td>TPP</td>
<td>2200</td>
</tr>
<tr>
<td>The ratio of the cost of power plant construction, r.u.</td>
<td>0.511628</td>
<td>0.255814</td>
</tr>
<tr>
<td>CFEP, kg CO$_2$-eq./MWh</td>
<td>11.86977</td>
<td>5.934884</td>
</tr>
</tbody>
</table>

### Fuel Production

The component of CFEP due to fuel production can be calculated using the formula:

$$c_2^E = c_2^{EL} + c_2^{EF} + c_2^{ES},$$  (4)

where $c_2^{EL}$, $c_2^{EF}$, $c_2^{ES}$ — the components of GHG caused, respectively, by GHG leakage in the process of fuel extraction; by burning fuel directly at fuel production enterprises; burning of fuel at power stations of the power system and in boiler houses for the production of electrical and thermal energy necessary for the production of fuel, kg CO$_2$-eq./n.u. s-th type of fuel.

When calculating according to formula (1) the value of the component of GHG caused by GHG leakage during its extraction, specific GHG leakage during its extraction can be calculated according to the formula:

$$a_{quv}^{EL} = C_{svu}^{EL} / E_{svu}^{EL},$$  (5)

where $C_{svu}^{EL}$ — emissions of the v-th type of GHG during the extraction of the q-th type of fuel, which is used for the production of the s-th type of fuel in the u-th country, t; $E_{svu}^{EL}$ — production volume of the q-th type of fuel in the u-th country, n.o. q-th type of fuel.

The fuel production quantities and GHG emissions can be determined from the latest national GHG inventory report which has been reviewed by the International expert review team on Verification of GHG Inventories of Countries Annex I UNFCCC (ERT).

The components of RES due to the burning of fuel at fuel production enterprises and due to the burning of fuel at power stations of the power system/in boiler houses for the production of electrical and thermal energy are calculated according to formula (2).

Nuclear fuel is not produced in Ukraine. Therefore, the value of the coefficient of GHG emissions when burning the nuclear fuel in formula (3) can be calculated from the estimate of GHG produced from nuclear fuel [8], using the formula:

$$k_{q=3 uv}^C = c_{q=3 uv} 10^{-3} / b_{q=3 uv},$$  (6)

where $c_{q=3}$ — CFEP generated from nuclear fuel, kg CO$_2$-eq./MWh; $b_{q=3}$ — specific consumption of
nuclear fuel during the production of electricity at the NPP, tce/MWh.

The specific consumption of nuclear fuel for the production of electricity in Ukraine in 2017 (which can be determined from the energy balance of Ukraine) was $b_{s-3} = 0.39718$ tce/MWh, and the CFEP generated from nuclear fuel is $c_{s-3} = 117.0$ kg CO$_2$-eq./MWh [8]. At the same time, the carbon footprint of nuclear fuel production can be estimated at the level of 0.29458 t of CO$_2$-eq./tce.

The specific consumption of the $q$-th type of fuel during the extraction of the $s$-th type of fuel at fuel production enterprises, as well as the fuel consumption at power stations of the power system and in boiler houses, for the production of electric and thermal energy, which are used for the production of electric and thermal energy at power stations of the power system and in boiler houses, kg ce/MWh and kg ce/Gcal; $W_{qu}^c$ and $Q_{qu}^c$ — volumes of use, respectively, of electrical and thermal energy in the production of the $q$-th type of fuel in the $u$-th country, MWh and Gcal; $W_{qu}^B$ and $Q_{qu}^B$ — own production, respectively, of electrical and thermal energy at enterprises producing the $q$-th type of fuel in the $u$-th country, MWh and Gcal.

Since nuclear fuel is not produced in Ukraine, the value of the GHG component caused by the production of nuclear fuel can be taken as estimated [8] at the level of 0.0223 t CO$_2$-eq./MWh.

### Fuel Transportation and Distribution

The component of CFEP, due to transportation and distribution of fuel, can be calculated by the formula:

$$c_s^T = c_s^{TW} + c_s^{TLT} + c_s^{TLD},$$

where $c_s^T$ — the component of CFEP caused by fuel transportation and distribution, kg CO$_2$-eq./MWh; $c_s^{TW}$, $c_s^{TLT}$, $c_s^{TLD}$ — components of CFEP, due, respectively, to the use of energy resources, GHG leakage in the process of transportation and in the process of distribution of the $s$-th type of fuel, kg CO$_2$-eq./MWh.

The component of the CFEP due to the use of energy resources can be calculated according to formula (2). At the same time, the specific consumption of the energy resource during fuel transportation can be calculated according to the formula:

$$a_{squ} = \frac{L_{su} b_{s-qu}^{TW}}{S},$$

where $q$ — the index of the type of energy resource used for fuel transportation; $L_{su}$ — the average distance over which fuel of the $s$-th type is transported in the $u$-th country, km; $b_{s-qu}^{TW}$ — specific consumption of the $q$-th type of fuel or energy resource for the transportation of the $s$-th type of fuel in the $u$-th country, n.u. $q$-th type of energy resource/km-n.u. $s$-th type of fuel.
Taking into account the calorific value and aggregate state of the three types of fuel considered in this paper, it can be concluded that the value of the GHG component during the transportation of fuel will be the largest during the transportation of hard coal. We will perform the calculation of the component of the CFEP used for the transportation of coal in Ukraine, using the following conservative assumptions, that the electricity produced at the TPP is used for the transportation of coal.

The specific consumption of electricity in railway transport in 2020 was 0.0112 kWh/(km·t) [12]. In order to estimate the value of magnitude of the component of the CFEP due to fuel transportation, we will calculate its approximate value assuming that electricity is produced at a TPP (which burns coal at an average specific consumption of 0.4011 tce/MWh (the Report of the State Committee of Statistics on the use and stocks of fuel in 2017) with a conversion factor $k_{s} = 0.75$ tce/t), and the average distance from mines to power plants (taking into account that Ukraine exports almost half of its coal) is 1000 km.

When using electricity to transport coal in formula (2), it is necessary to accept, formula:

$$k_{su}^c = c_{su},$$

where $c_{su}$ — the CFEP using the $q$-th type of fuel in the $u$-th country, kg CO$_2$-eq./MWh.

Taking into account the given data, the component of CFEP caused by coal transportation can be estimated at the level of 0.743 kg CO$_2$-eq./MWh (see Table 4) or 0.072 % of the amount of CFEP produced at the TPP.

GHG emissions during the transportation of natural gas and nuclear fuel can be neglected.

GHG leakage during fuel transportation and distribution occur only in the case of natural gas. Ukraine imports a significant amount of natural gas. The CFEP component due to GHG leakage in the process of its transportation and distribution can be calculated using formula (1). At the same time, specific GHG emissions during transportation and distribution of natural gas can be calculated using the following formulas:

$$a_{su}^{TL} = C_{su}^{TL}/E_{su}^{TL},$$

$$a_{su}^{TD} = C_{su}^{TD}/E_{su}^{TD},$$

where $a_{su}^{TL}$ — specific emissions of GHG during natural gas transportation, t of GHG of the $v$-th type/n.u. $s$-th type of fuel; $a_{su}^{TD}$ — specific emissions of GHG during the distribution of natural gas, t of GHG of the $v$-th type/n.u. $s$-th type of fuel; $C_{su}^{TL}$ and $C_{su}^{TD}$ — leakage of the $v$-th type of GHG, respectively, during transportation and distribution of the $s$-th type of fuel (in this case, natural gas) in the $u$-th country, t; $E_{su}^{TL}$ and $E_{su}^{TD}$ — volumes of transportation and distribution of the $s$-th type of fuel (in this case, natural gas) in the $u$-th country, n.u. $s$-th type of fuel.

Volumes of natural gas transportation and GHG leaks in the process of its transportation can be determined based on data from national GHG inventory reports.

GHG emissions of the of nuclear fuel transportation are absent and are not estimated in [8].

**Electricity Production**

The component of RES due to the burning of hard coal and natural gas for the production of electricity can be calculated according to formula (2). Since in this case fuel burning occurs directly for the production of electricity ($a_{su} = 1$) and only in one country — Ukraine ($u = 1$), formula (2) is simplified to the form, as indicated in formula:

$$c_p = \frac{b_d k_c F_p}{10^3 k_z'},$$

where $k_c^c$ — the coefficient of GHG emissions when burning the $s$-th type of fuel, t CO$_2$-eq./n.u. $s$-th type of fuel.
GHG emissions do not occur when burning nuclear fuel. However, GHG emissions during electricity production at the NPP (due to operation, maintenance and reconstruction of the NPP) are estimated at 24.5 kg CO$_2$-eq./MWh [8].

Handling of Electricity Production Waste

The component of GHG caused by the handling of electricity production waste depends on energy costs for storage of spent nuclear fuel, removal of waste from coal burning to the place of processing and disposal, etc. At the same time, it is necessary to take into account the effect of replacing raw materials and materials with electricity production waste in other sectors of the economy, where this occurs (for example, when using TPP slag in road construction).

Coal-burning power generation waste (slag that accumulates in ash and slag landfills) has recently been increasingly used for the production of slag gravel or slag blocks. There is practically no waste from electricity production when burning natural gas. Therefore, the component of GHG caused by the handling of electricity production waste at TPPs and CHPs can be disregarded.

The component of the CFEP at the NPP due to handling waste is determined by activities with spent nuclear fuel. The carbon footprint of the decommissioning and dismantling of the NPP is 47 kg CO$_2$-eq./MWh [8].

Initial Data and Results of Calculations from the Assessment of the Carbon Footprint of Electricity Production

In the article, calculations were made to estimate the average value of the GHG produced at TPPs and CHPs using hard coal and natural gas in Ukraine, according to statistical data of 2017.

Nuclear fuel is not produced in Ukraine. That is why the calculations of the CFEP were performed only for hard coal and natural gas in this publication.

The following assumptions were made when performing the calculations:

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- the import of electricity was not taken into account (in 2017, it accounted for 0.033 % of the total electricity production in Ukraine, according to the State Statistics Agency);
- coal, natural gas and nuclear fuel were imported from only one country;
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- specific fuel costs for fuel production in Ukraine and in the exporting country are the same;
- the initial data for the calculations of the CFEP when burning hard coal and natural gas for the production of electricity were taken from statistical data, respectively, for TPPs and CHPs.

In the Tables 2–4 show the initial data and results of calculations of the components of CFEP in Ukraine when using hard coal and natural gas, prepared on the basis of statistical data of 2017. Data in the Table 2 was prepared based on the information of statistical Form 11-MTP, National GHG inventory reports [13] and work [14]; Table 3 — according to the statistical Form 4-MTP. The Table 3 also shows data [8] on the production of electricity using nuclear fuel, since electricity, produced at the NPP of Ukraine, also used in the production of fuel. In the Table 5 shown comparative data on the CFEP which is produced with hard coal and natural gas.

The big difference between the results of CFEP calculations in Ukraine and the data [6, 7] when burning hard coal can be explained by the different of technical condition of power plant equipment in Ukraine and in abroad countries and calculation methods, in particular, the use of different limits of the life cycle of electricity production. Although the results of calculations of GHG emissions during coal burning in Ukraine are closer to the US data [15]. Regarding the burning of natural gas, it can be noted that, in addition to the different level of technical condition of power plant equipment (and natural gas is used in the combined production of heat and electricity), the difference in data may be due to the use of different methods of distributing fuel consumption for the production of heat and electricity. As is known, these costs are distributed using energy and economic analysis [16]. In [17], the enthalpy indicator is also used for this distribution. Therefore, data on the specific consumption of natural gas in different countries and for different types of equipment lie within wide limits — from 171.4 to 291.1 kg of natural gas per MW h (in particular, for the USA — from 179.4 to 184.5 kg fuel/MWh), which is significantly less than at domestic power plants — from 281.8 to 390.2 kg of fuel/MWh [18].

Conclusions

The method proposed in the article meets the requirements of the ISO 14067 standard and can
Table 2. Data for calculation CFEP in Ukraine, 2017

<table>
<thead>
<tr>
<th>Name of quantities and units of measurement</th>
<th>The values for power plants that are used to produce electricity are burned</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal (s = 1)</td>
</tr>
<tr>
<td>Volumes of electricity production in Ukraine, GWh</td>
<td>41113226.00</td>
</tr>
<tr>
<td>Coefficient of carbon dioxide emissions during fuel combustion in Ukraine, t CO\textsubscript{2}-eq./t; t CO\textsubscript{2}-eq./thousand m\textsuperscript{3}; t CO\textsubscript{2}-eq./tce</td>
<td>2.00</td>
</tr>
<tr>
<td>Coefficient of carbon dioxide emissions during fuel combustion in Ukraine, t CH\textsubscript{4}/t; t CH\textsubscript{4}/thousand m\textsuperscript{3}; t CH\textsubscript{4}/tce</td>
<td>2.15 \times 10\textsuperscript{-5}</td>
</tr>
<tr>
<td>Coefficient of carbon dioxide emissions during fuel combustion in Ukraine, t N\textsubscript{2}O/t; t N\textsubscript{2}O/thousand m\textsuperscript{3}; t N\textsubscript{2}O/tce</td>
<td>3.22 \times 10\textsuperscript{-5}</td>
</tr>
<tr>
<td>The share of imported fuel, r.u.</td>
<td>0.46</td>
</tr>
<tr>
<td>Coefficient of conversion of fuel volumes from natural units to conventional fuel, tce/t; tce/thousand m\textsuperscript{3}</td>
<td>0.75</td>
</tr>
<tr>
<td>Specific consumption of the fuel type for electricity production, tce/MWh</td>
<td>0.39</td>
</tr>
<tr>
<td>General leakage of GHG during fuel production in Ukraine, t CO\textsubscript{2}-eq.</td>
<td>11679274.02</td>
</tr>
<tr>
<td>General leakage of GHG during fuel production in exporting country, t CO\textsubscript{2}-eq.</td>
<td>63840.75216</td>
</tr>
<tr>
<td>Fuel production in Ukraine, t; thousand m\textsuperscript{3}</td>
<td>24200000.00</td>
</tr>
<tr>
<td>Fuel production in exporting country, t; thousand m\textsuperscript{3}</td>
<td>411113000.00</td>
</tr>
<tr>
<td>General leakage of GHG during natural gas transportation in Ukraine, t CO\textsubscript{2}-eq.</td>
<td>663910.53</td>
</tr>
<tr>
<td>General leakage of GHG during natural gas transportation in exporting country, t CO\textsubscript{2}-eq.</td>
<td>27902977.36</td>
</tr>
<tr>
<td>Volumes of natural gas transportation in Ukraine, thousand m\textsuperscript{3}</td>
<td>140698163.90</td>
</tr>
<tr>
<td>Volumes of natural gas transportation in exporting country, thousand m\textsuperscript{3}</td>
<td>639500000.00</td>
</tr>
<tr>
<td>General leakage of GHG during natural gas distribution in Ukraine, t CO\textsubscript{2}-eq.</td>
<td>12424104.02</td>
</tr>
<tr>
<td>Volumes of distribution of natural gas in Ukraine, thousand m\textsuperscript{3}</td>
<td>37086174.61</td>
</tr>
</tbody>
</table>

Table 3. Volumes of use of hard coal, natural gas and nuclear fuel for fuel production in Ukraine in 2017

<table>
<thead>
<tr>
<th>Name of quantities and units of measurement</th>
<th>Type of fuel (s)</th>
<th>Values for fuel types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coal (q = 1)</td>
<td>natural gas (q = 2)</td>
</tr>
<tr>
<td>Volumes of fuel use at production enterprises, tons; thousand m\textsuperscript{3}</td>
<td>coal</td>
<td>198058.30</td>
</tr>
<tr>
<td></td>
<td>natural gas</td>
<td>8915.90</td>
</tr>
<tr>
<td>Volumes of fuel use in the energy system and in boiler houses, tons; thousand m\textsuperscript{3}; tce</td>
<td>coal</td>
<td>436938.29</td>
</tr>
<tr>
<td></td>
<td>natural gas</td>
<td>13940.98</td>
</tr>
</tbody>
</table>
Table 4. Results of calculations of the average value of the carbon footprint of electricity production in Ukraine using hard coal and natural gas in 2017, kg CO₂-eq./MWh

<table>
<thead>
<tr>
<th>The components of CFEP are determined</th>
<th>The values for power plants that are used to produce electricity are burned</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coal ((s = 1))</td>
</tr>
<tr>
<td>Construction of power plants</td>
<td>11.87</td>
</tr>
<tr>
<td>Extraction and production of fuel</td>
<td>180.34</td>
</tr>
<tr>
<td>Including GHG leakage during fuel combustion:</td>
<td>134.76</td>
</tr>
<tr>
<td>- at enterprises</td>
<td>13.64</td>
</tr>
<tr>
<td>- at power stations and boiler houses</td>
<td>32.00</td>
</tr>
<tr>
<td>Fuel transportation and distribution</td>
<td>0.743</td>
</tr>
<tr>
<td>Including electricity consumption during coal transportation:</td>
<td>0.743</td>
</tr>
<tr>
<td>- GHG leakage during natural gas transportation</td>
<td></td>
</tr>
<tr>
<td>- GHG leakage during natural gas distribution</td>
<td></td>
</tr>
<tr>
<td>Fuel burning during electricity production</td>
<td>1046.98</td>
</tr>
<tr>
<td>Handling of electricity production waste</td>
<td></td>
</tr>
<tr>
<td>In total</td>
<td>1240.01</td>
</tr>
</tbody>
</table>

Table 5. The carbon footprint of electricity production, kg CO₂-eq./MWh

<table>
<thead>
<tr>
<th>Fuel</th>
<th>CFEP</th>
<th>GHG Emission from fuel combustion at a power plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>National data</td>
<td>International data ([6, 7])</td>
</tr>
<tr>
<td>Coal</td>
<td>1240</td>
<td>840–910</td>
</tr>
<tr>
<td>Nature gas</td>
<td>699.5</td>
<td>490–650</td>
</tr>
</tbody>
</table>

be used to calculate the CFEP produced using all types of fuel.

The paper calculates the average value of CFEP according to statistical data of Ukraine in 2017 when using hard coal (which is 1240 kg CO₂-eq./MWh) and natural gas (699.45 kg CO₂-eq./MWh taking into account literature data on the CFEP produced at the NPP (which is estimated at 117.00 kg CO₂-eq./MWh).

GHG emissions during electricity production using natural gas are 1.8 times lower than when using hard coal, and when using nuclear fuel — 10.6 times lower than when using hard coal and 6 times lower than when using natural gas.

GHG emissions that occur during the combustion of fuel for electricity production with hard coal amount to 1047 kg CO₂-eq./MWh (or 84.4 % of the total GHG emissions during electricity production), and when burning natural gas — 558.36 kg CO₂-eq./MWh (or 80 % of total GHG emissions during electricity production).

The paper compares the results of calculations with data from literary sources and provides an explanation for the excess of the carbon footprint of electricity production, which is produced using hard coal and natural gas at power plants in Ukraine with similar indicators in other countries. The difference in indicators may be due to different levels of technical condition of power plant equipment, different calculation methods (in particular, the use of different limits of the life cycle of electricity production and the distribution of fuel costs for the production of heat and electricity in their combined production).

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Вуглецевий слід виробництва електроенергії

Розроблено методику розрахунку вуглецевого сліду виробництва електроенергії, яка відповідає вимогам стандарту ISO 14067 та методам інвентаризації викідів парникових газів Міжнародної групи експертів зі зміни клімату. Виконано розрахунки вуглецевого сліду виробництва електроенергії при використанні кам'яного вугілля та природного газу, а також його складових для усіх етапів виробництва електроенергії: при будівництві електростанцій, видобутку палива та транспортуванні палива, виробництві та транспортуванні електроенергії, поводженні з відходами її виробництва. Оскільки в розробленій методиці не враховуються втрати при передачі та розподілі електроенергії, в даній публікації використовується термін вуглецевий слід виробництва електроенергії, а не вуглецевий слід електроенергії, щоб підкреслити, що у даному випадку йдеться про вуглецевий слід електроенергії на ширинах електростанцій. Порівняння результатів розрахунків з літературними даними показало значне перевищення вуглецевого сліду виробництва електроенергії на електростанціях України. Зроблено припущення, що причини цього перевищення полягають не лише в різномірному технічному стану обладнання електростанцій, а й в застосуванні різних методів розрахунку, зокрема різних методів розподілу витрат палива на виробництво теплової та електричної енергії при їх комбінованому виробництві, та різних меж життєвого циклу виробництва електроенергії. Окінчається, що результати роботи будуть застосовуватися в розрахунках величини вуглецевого сліду продукції, у виробництві якої використовується електрична енергія. Бібл. 18, Табл. 5.

Ключові слова: парникові гази, вуглецевий слід виробництва електроенергії, питомі витрати палива, кам’яне вугілля, природний газ.

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