GREENHOUSE GAS EMISSION INVENTORY IN UKRAINE'S CEMENT SECTOR

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Summary

This report presents the results of an inventory of greenhouse gases (GHGs) in Ukraine's cement sector. The GHG sources include CO_2 from the calcination process and CO_2, CH_4, and N_2O from fuel combusted to provide the high-temperatures needed for the calcination process. The study was accomplished to comply with Ukrainian commitments to the international process of GHG mitigation. These findings also identify opportunities to significantly improve the energy efficiency of the Ukrainian economy.

The cement sector of Ukraine, one of several industries manufacturing construction materials, makes a considerable contribution to anthropogenic GHG releases and the corresponding effect on climate change. The inventory of GHG emissions was estimated for 2001 for each of Ukraine's Oblasts and the Autonomous Republic (AR) of Crimea. Experts also specified CO_2 emission factors for the calcination process for all cement types produced in Ukraine.

Estimations show, that GHG emissions from the calcination process total 2.3 million tonnes of CO_2-equivalent plus 1.7 million tonnes of CO_2-equivalent from fuel combustion, for a total of 4.0 million tonnes of CO_2-equivalent. The report also estimates that the GHG reduction potential by shifting from the wet to dry cement production process is 811 thousand tonnes of CO_2-equivalent, which is over 20% of total CO_2-equivalent emissions.

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Introduction

In June 1992, more than 150 countries signed the Framework Convention on Climate Change (FCCC) at the Earth Summit in Rio de Janeiro. The Convention entered into force in 1994 after 50 signatories had officially ratified the agreement. The FCCC requires signatories to prepare inventories of their greenhouse gas emissions and sinks. While Ukraine is the 11th largest emitter of greenhouse gases, it's current emissions are well below their 1990 level due to the economic recession in the 1990s. Ukraine submitted its first draft inventory to the FCCC Secretariat in the fall of 1999. Monitoring and reporting greenhouse gas emissions are both key elements of compliance with the FCCC, which requires that Ukraine constantly investigate, develop inventories, and monitor emissions.

Complying with FCCC commitments is a compulsory precondition for Ukraine to participate in the international process of GHG mitigation. Realization of these commitments will allow Ukraine to estimate it's GHG reduction potential, and implement energy efficiency projects and other activities related to reduction of GHG emissions. An added benefit is that this will allow Ukraine to significantly improve the energy efficiency of its economy.

Two factors impinge on Ukraine's ability to prepare accurate inventories of GHGs. The first is the lack of statistical data, which makes it extremely difficult to prepare transparent, IPCC-compatible inventories. The second is lack of familiarity with international greenhouse gas inventories at the local level, where data are initially collected. As part of complying with Ukraine's FCCC commitments, the U.S. Environmental Protection Agency, through the Pacific Northwest National Laboratory, has requested the Agency for Rational Energy Use and Ecology to inventory GHGs in Ukraine's cement sector.

IPCC guidelines indicate that, worldwide, the cement industry produces approximately 2.4% of global GHG emissions from industrial processes (IPCC, 1996). In turn, the cement industry in Ukraine makes a considerable contribution to GHG emissions. In 1990 Ukraine's cement sector produced 9 million tonnes of CO_2 emissions from physical and chemical calcination processes [16] or about 8.4% of Ukraine's GHG emissions from industrial processes. In addition to CO_2 emissions from the calcination process for cement production, the cement sector also produces GHG emissions from fuel combustion necessary for the high-temperature calcination process.

Under this project ARENA-ECO's experts prepared a comprehensive GHG inventory for the cement sector of Ukraine based on experience [1,2] to include an inventory of CO_2 emissions from the calcination processes and an inventory of GHG emission from fuel combustion for the high-temperature calcination process. This report presents the following results:

- Proposed comprehensive GHG emission estimation methodology for the cement sector of Ukraine adopted to the national conditions, using existing GHG inventory methodologies for this sector.
- Proposed methodology and calculation of factors for CO_2 emissions from the calcination process;
- Estimated GHG emissions in 2001 for Ukraine's cement sector that includes the Autonomous Republic Crimea and Ukrainian Oblasts for both CO_2 emissions from the calcination process and emissions from fuel combustion.
- Estimated GHG reduction potential by shifting from the wet to dry cement production method.

1. Characteristics of GHG inventory object

1.1. General information

The report 'Proposals to a concept of the Ukrainian National GHG Inventory System' [14] suggested terms for inventorying and categorizing the key sources of GHG emissions in order to provide Ukraine the opportunity to participate in international activities for climate change mitigation. In accordance with 'Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories' [2] the key source categories of GHG emissions include the economic sectors, which with 90% probability, account for 95% of total GHG emissions in Ukraine. Fuel combustion in the energy sector produces the largest amount of GHG emissions, followed by industrial processes, agriculture, changes in land use, and forestry.

Cement production, along with walling, decoration, and roofing materials, is one of the main branches of the construction materials industry that is the focus of growth in construction. In 1990, the GHG emissions from the calcination process were approximately 9 million tonnes of CO_2 or over 8% of industrial CO_2 emissions in Ukraine. The economic recession and structural reform in the 1990s led to a reduction in Ukraine's cement production, which decreased CO_2 emissions to 2.6 million tonnes or 5.3% of Ukraine's total industrial CO_2 emissions. Economic growth has increased during the last few years, which makes it reasonable to expect growth in Ukraine's cement production.

In addition to CO_2 emissions from the calcination process, fuel is consumed to produce the high-temperatures needed for calcination. This fuel consumption produces GHG emissions almost equal in magnitude to the CO_2 emissions from calcination and is the source of the greatest potential reduction in emissions in Ukraine's cement sector.

1.2. Products of the Ukrainian cement sector

Cement (from Latin Caementum – crushed stone) belongs to the group of non-organic powder-like binding materials [4]. It is one of the most important building materials used for production of concrete and building mixtures, binding separate elements (details) of constructions, producing hydro-insulation, and other materials.

Cements are produced from calcination, which heats a mixture of ground mineral additives that contains certain proportions CaO, SiO_2, AI_2O_3 and FeO. Proportions of these components determine the main properties of the different types of cement. When mixed with water, a plastic and viscous dough is produced, which hardens owing to its physical and chemical properties, and turns into a stone like substance that preserves its strength in air and water environments.

The following cement types were produced in Ukraine in 2001:

1) Cements that are used for common construction purposes:

- Portland cement;
- Blended Portland cement that contains:
- Asbestos-cement products;
- Slag Portland cement;
- Fast-hardening cement;
- Road cement;
- Cement types that do not require forming.

2) Sulfate and frost-resistant cements [6] that are used [9] for construction periodically subject to conditions of sulfate aggression, freezing and defrosting, and damping and drying:

- Sulfate-resistant Portland cement;
- Sulfate-resistant slag Portland cement.

3) Oil-well Portland cements that are used [9] for plugging petroleum and gas bores and are characterized by fast bondability and slow hardening [8]:

- Oil-well Portland cement without additives.

4) Alumina cements that are used where fast hardening is needed and in extreme environments [17, 18]:

- Alumina cement is used [9] for urgent and emergency repair, rehabilitation, buildings exposed to mineralized water or sulphur trioxide, and for heat-resistant concretes and mortars. Alumina cement is not used in high-temperature or humid conditions. This cement is characterized fast hardening at normal and low temperatures, and resistant to mineralized water;
- Gypsum and alumina expanding cement is used [9] for waterproof concretes and mortars, sealing, repairing, and plugging petroleum and gas bores. This cement expands when setting, hardens fast, has high density, and is waterproof and sulfate-resistant.

In order to estimate the inventory CO_2 emissions from the calcination process, it is necessary to have the information on the types of cement, their composition, and the amount and composition of the clinker (CaO) component

1.3. Technologies of cement production in Ukraine

Cementis is known from the time of ancient Egypt and Kievan Rus [3]. The first cement, Roman cement, is known to have been invented in England in 1796 by G. Parker who received a license for hydraulic binding using Roman cement made from burnt marl. In 1824 G. Aspdin in England and in 1825 Y. Cheliev in Russia invented Portland cement, produced by a mixture of burnt lime and clay, independently of each other. Other types of cement invented were made from various additions of Portland cement and lime, these include high-grade Portland cement, Pozzolan and Trass Portland cement, Slag Portland cement, Ore, White, Barrit, Anhydrite, Lime-Pozzolan, Alumina, Lime-Ashy, Lime-Slag, and Non-clinker Slag cements.

Cement is produced from geological materials that contain CaO, SiO_2, AI_2O_3 and FeO in certain proportions to define the main properties of the cement. The following materials may be used for cement production [3]:

a) natural marls, cement marl [4],and sedimentary rock, which is a homogeneous mixture of 75-80% $CaCO_3$ and 20-25% clay. These materials can be used without any additives for production of Portland cement;

b) mixtures of hard and soft limes (sendimentary carbonate rocks predominantly of marine origin, with $CaCO_3$ as the main mineral) [4], and certain compositions of chalk and clay free of SO_3 and $MgCO_3$;

c) mixtures of marl limes that contain 83-94% $CaCO_3$, clay marls that contain 55-75% $CaCO_3$, or marls that contain 12.5-55% $CaCO_3$;

d) mixtures of lime or chalk, and grainy blast-furnace slag.

The clay component is usually added in form of fusible clay or loam, and rarely shale. The following additives are used if required: silica (quartz sand, flask, tripoli), alumina (bauxite, alumina clays), or iron ores. The proportion of lime and clay is 3:1 on average in terms of mass and in terms their physical properties the raw materials are split into hard (hard limes and marls), soft (chalk), and fuzzy (marls and clays).

The stages of cement production are:

- Grinding raw components.
- Milling and mixing (dosing) the raw mixture components, and producing raw flour for dry cement production or slurry for wet cement production.

- Calcination, which involves baking the raw mixture to produce the cement clinker.
- Cooling and grinding clinker with necessary additives to produce cement.

The most wide-spread technologies of cement production are wet and dry. The difference is that in the wet technology, the raw materials are mixed with water in the crushing stage to reduce their hardness for the grinding process.

Cement properties are improved with the addition of gypsum derived from sedimentary geological material, with gypsum as the main rock-forming mineral (about 5-7%) and 15% of natural active additives [3]. Natural active additives include: sedimentary rocks (tufs, porous carbonate rock formed from low-temperature hydrothermal solutions with $CaCO_3$ as the main rock-forming mineral [4]), tuf lava, volcanic ash, and holystone. Clay rocks produced during underground fires in coal beds are rarely used as an additive, but may be used as an active mineral additive for Portland cement [4].

We will provide a short review of the chemical reactions for producing Portland cement clinkers [3]. A mixture of raw material, which undergoes special treatment, is placed in a kiln under conditions of increasing temperature. The raw materials are dried first and then dehydrated at temperatures of 550-800° to form aluminosilicate. This phase produces a loose structure of particles with increased internal energy and reactivity.

A reaction begins at 820 ^{0}C that decomposes chalk ($CaCO_3$) into CaO and CO_2, and ends at 907 ^{0}C. Simultaneously the reaction between the calcium oxides (CaO) and products of clay dehydration, which contain mainly aluminum oxides and silicon oxides, begins. Single lime aluminate ($CaO \cdot Al_2O_3$) and single lime silicates are formed at temperatures of about 800^{0}C ($CaO \cdot SiO_2$) from the CaO in the lime and the SiO_2 and AI_2O_3 in the clay. Subsequently, at 900^{0}C, the $CaO \cdot SiO_2$ is enriched with the lime and gradually transforms into two-lime silicate ($2CaO \cdot SiO_2$), and finally at 1,150^{0}C lime (CaO) ceases to exist as a reacting substance. Simultaneously, $CaO \cdot AI_2O_3$ is transformed into two lime silicates ($2CaO \cdot AI_2O_3$).

Reactivity increases at temperatures of 1,200-1,250 ^{0}C and two-lime ferrite $2CaO \cdot Fe_2O_3$, is formed, which induces a liquid phase that is a solution of particles of charged materials that have not reacted. These processes lead to supersaturation and crystallization of three lime silicates ($3CaO \cdot SiO_2$), the main artificial mineral of cement clinkers, which is a compact mass consisting of particles 4-20 mm in size.

The clinker mass is quenched in a special refrigerator to prevent formation of large crystals and preserve the material in a non-crystalline glass-like state, which maintains the internal energy of cement. Cement produced from non-quenched clinkers will have reduced reactivity with water.

At the next stage, the clinker is finely ground and mixed with gypsum and active mineral additives or other materials to produce cements having specific properties.

The cement industry is one of the first to deal with dust (Cement Kiln Dust – CKD) removal techniques that have grown in number to include:

- Reduce the velocity of dusty air so that the dust particles settle out of the air-stream;
- Filter the dust from the air-stream;
- Apply centrifugal force to the air-stream to 'trap' the heavier dust particles.
- Subject the air-stream to electrostatic precipitation that removes 98-99% of the dust particles by applying an electric charge to the dust particles, causing them to be attracted to an opposite charge and precipitated out of the air-stream.

Depending on the mixture and preparation of the raw materials, the calcination process may use a dry technology in a rotary kiln, a wet technology in a rotary kilns, or a rarely used combined technology. The selection of the calcination technology is based on a mix of technical and economic indicators that include the concentrations of the raw materials, the consumption of fuel

and electricity, and labor. Irrespective of the technology it is always necessary to provide a finely ground and homogenous mix of raw materials, which influences the clinker quality, because as the density of the clinker becomes higher, the reactions between the raw materials become more intensive.

In the dry technology process [7], the raw materials are dried and then transformed into dry flour by crushing and grinding. The flour is then placed in the kiln for calcination. The dry technology process consumes more electricity, which is explained by the requirement to crush the raw materials components.

The wet technology utilizes water in the crushing and grinding process to produce a slurry that contains 32-45% water and is the consistency of cream. The water reduces the energy consumption at this stage by reducing the hardness of the inputs and improving the grind-ability of the constituents, but requires more energy at the kiln stage as it must be evaporated away.

Advantages of the wet process [3] include:

- A more homogenous mixture that provides a more consistent and constant higher quality final product;
- Improvement in more hygienic working conditions because preparation and transportation of slurry is not accompanied with dust release;
- Lower capital costs because the production equipment is less sophisticated and costly.

On the other hand, the wet process requires higher energy consumption for the calcination process.

2. GHG inventory methodology for cement production in Ukraine

2.1.General information

There are several methodologies to develop an inventory of GHG emissions from cement production:

- IPCC Guidelines [1];
- IPCC Good Practice Guidance [2];
- The methodology proposed by GHG Protocol Initiative based on clinker [10] and cement [11] production data.

Characteristics of these three methodologies are provided below:

Depending on the inventory objective and specification of the available statistics, the inventory of estimated GHG emissions from cement production might be performed for three specification levels:

1) GHG emissions based on total cement production – all factors are derived from IPCC Guidelines;
2) GHG emissions based on the production technology and volume of clinker production. It is possible to specify the relevant emission factors, provided that the statistical information is available, otherwise IPCC factors are used. Since the State Committee of Statistics of Ukraine does not provide information on the lost CKD, the IPCC CKD correction factor 1.05 was used to estimate CO_2 emissions from production of clinker, which is lost as CKD.
3) GHG emissions based on clinker production data from the separate enterprises – all IPCC factors are specified given the specific technological characteristics of the separate enterprises.

Based on the principals presented in the IPCC methodology [1], more detailed methodologies for estimating GHG emissions were developed [2, 10, 11]:

- Good Practice [2], specifies clinker and cement-based GHG emission estimation methodologies and recommends how to specify factors given the available statistics and the default CKD correction factor;
- The GHG Protocol Initiative proposes two methodologies based on the IPCC Good Practice Guidelines that recognize data availability constraints [2]. One is a clinker-based methodology presented in the WBCSD "Cement CO_2 Protocol" [10]. This estimation tool is written for cement companies to control and report on direct and indirect greenhouse gas emissions resulting from cement production at their facility. The second is a cement based methodology developed under the U.S. EPA's Climate Wise program [11] that enables plant mangers to facilitate the measurement and reporting of CO_2 emissions from cement production. The objective of the latter methodology is to ensure consistency of GHG inventories for cement production according to the IPCC Guidelines.

IPCC Guidelines [1] define requirements to estimate national inventories of GHGs. The main objective of the Guidelines is to clearly define the consequence of estimation, record the results to adhere to a common inventory format in various countries and regions, and facilitate comparison of the conclusions and reliability of the estimation process. Given the available statistics it is proposed to perform estimation based on the clinker or cement production, with specification of associated CO_2 emission factors.

This report proposes a comprehensive approach [19] to inventory cement sector GHG emissions based on the experience of [1; 2]. It recommends a separate estimation procedures for the CO_2 emissions for the calcination process for each type of cement and for the fuel combusted to provide the high temperatures needed for calcination.

The methodology [19] considers the IPCC recommendations related to specifying factors for CO_2 emissions from the calcination processes and, additionally, determines the emission factors specific to the content of clinkers for all types of cement produced in Ukraine.

The CO_2 emission factors are based on the assumption that all CaO is released from the raw carbonate (i.e. lime $CaCO_3$) in the calcinations process and are linearly related to the CaO content of the clinker.

2.2. CO_2 inventory methodology for calcination process

This section describes the GHG emission estimation methodologies for the cement sector of Ukraine, using a comprehensive approach. In this approach, CO_2 emissions are estimated for Ukraine's cement industry based on the production of each cement type, the CaO content in clinker, and the clinker content in cement, as well as CaO content in clinker.

The estimates of CO_2 emissions for each cement type utilize the following information and steps:

- determine cement production by administrative units of Ukrainian (Autonomous Republic of Crimea, Kyiv,and Oblasts);
- determine clinker content in each type of cement;
- determine CaO content in clinker for each cement type;
- calculate CO_2 emission factor;
- consider CO_2 emissions from production of clinkers lost as CKD;
- calculate CO_2 emissions.

$$V^*_{ri} = M_{ri}\ k_{cli}\ K^{cl}_{CO_2} k_{CKD}, \qquad (1)$$

where,
V^*_{ri} – CO_2 emissions, Gg;
r – index of administrative unit;
i – type of cement;

M_{ri} - each type of cement produced in Ukraine (tonne);
k_{cli} –fraction of clinker in each cement;
$K^{cl}_{CO_2}$ – CO_2 inventory factors for calcination process, t CO_2/t clinker;
k_{CKD} – default correction factor CKD correction factor for CO_2 emissions, relative units.

2.3. Inventory methodology for GHGs emitted from fuel combusted for high-temperature calcination process

An inventory of emissions of CO_2, CH_4, and N_2O are estimated from the fuel combusted during the high-temperature calcination process are presented in this section based on the IPCC methodology [1].

This methodology for estimating CO_2 emissions from fuel combustion utilizes the following information and steps:

- estimate of apparent fuel combustion in terms of coal-equivalent;
- convert into a common energy units;
- multiply by emission factor to compute the carbon content;
- compute stored carbon;
- correct for unoxidised carbon;
- convert oxidized carbon to CO_2 emissions.

In general CO_2 emissions from fuel combustion are calculated based on the following formula:

$$V_{ri} = E_i \, Kc_i \, L_i, \tag{2}$$

where,

V – CO_2 emissions Gg;
r – index of administrative unit;
i – fuel type;
E_i – combusted i-type fossil fuel, t.c.e.;
Kc_i – CO_2 emission factor for i-type fossil fuel tC/TJ;
L_i – oxidized carbon fraction for i-type of fossil fuel, relative units.

Methane (CH_4) and nitrous oxide (N_2O) and other GHG emissions are also released during fuel combustion. The quantity of these emissions depends on fuel type, technology of fuel combustion, operation, and service life of equipment. The IPCC methodology [1] separates these emissions by four fuel types to facilitate estimation of these GHG emissions:

- coal;
- natural gas;
- oil, including transport gasoline, transport diesel oil, other oil products;
- biomass, including wood and wood waste, charcoal, other biomass and wastes.

The methodology [1] estimates CH_4 and N_2O emissions from fuel combustion in the following steps:

- estimate quantities of fuel, by type, consumed to provide high temperature calcination administrative units;
- estimate emission factors for each fuel;
- estimate emissions.

In general CH_4 and N_2O emission are calculated based on the following formula:

$$V_{ij} = E_i \, K_{ij}, \tag{3}$$

where,

j – index of GHG (methane or nitrous oxide);

i – fuel type;
V_{ij} – GHG emissions, Gg;
E_i – consumed fossil fuel, TJ;
K_{ij} – GHG emission factor.

3. Initial data

3.1. Information sources

As already mentioned, GHG emissions in the cement sector of Ukraine are determined by the calcination process and fuel combustion to provide the necessary high temperature conditions for calcination. That is why it is necessary to possess the following data:

- amount of cement production, by type;
- content of cement clinker, by type of clinker;
- content of CaO in clinker;
- amount of fuel combusted to provide the high temperature conditions for calcination.

The sources of information for preparation of this data are:

- Form 1-p "Enterprise's report on production" [12] – cement production data at the oblast and national levels;
- Form 11-MTP "Report on the results of fuel, heat and electricity consumption" [13] – energy consumption data in the cement sector at the oblast and national levels;
- State standards of Ukraine (DSTU);
- Technological regulations.

Form 1-p contains data on total cement production in natural units (net weight of production without packing) by administrative unit in Ukraine. A subsection of this form contains data on the total amount of cement production by type.

Form 11-MTP contains information on the total amount and specific fuel combustion (t.c.e.) for cement production by administrative units of Ukraine. This form also contains data on fuel combustion exclusively to provide the necessary high temperature conditions for calcination. Fuel combustion data by type of cement is not presented in form 11-MTP.

DSTU established the content of clinker in cement and content of CaO in clinker. The ranges in the values established by DSTU are wide, which introduces a high level of uncertainty in the inventories based on these values. Therefore, to improve the accuracy of CO_2 emissions from the technology process it is better to use the technological regulations of some enterprises.

The most universal source of primary data are the technological regulations that can provide all of the data at the enterprise level, but due to legal limitations for confidentiality reasons, the State Committee of Statistics of Ukraine does not provide this information at the enterprise level. However, study results show that the content of clinker in cements and content of CaO in clinkers, as determined by the Ukrainian enterprises, is within narrower limits. Further, the clinker content in cement and CaO content in clinker is quite stable for each cement type and, for all practical purposes, doesn't depend on the enterprise where is the cement is produced. Thus, it is recommended to define clinker content in cement and CaO content in clinker based on the results of the analysis of technological regulations, which are performed periodically (once every several years) by experts in this field.

The methodologies for calculating GHG emissions from calcination and fuel combustion in the cement sector are described in sections 3.2. and 3.3, respectively.

3.2. GHG emission factors

3.2.1. Estimated CO_2 emission factors from calcination processes

Each type of cement clinker consists of different minerals, from which a CO_2 emission factor may be specified by using the atomic mass of the chemical components of the minerals for the calcination process. In general, the CO_2 estimation factor for calcination is specified based on the information related to clinker production, using the following formula:

$$K_{CO_2}^{cl} = 0.785 \sum \delta_i \xi_i \quad (4)$$

where,

$K_{CO_2}^{cl}$ – CO_2 inventory factors for calcination process, relative units;
0.785 – ratio of molecular weight of CO_2 and CaO, relative units;
i – index of artificial mineral, that contained in clinker;
δ_i – content of CaO in *i*-mineral, relative units;
ξ_i – content of each artificial mineral in clinker, relative units.

The CaO content in each artificial mineral contained in the clinker is estimated based on the molecular weight of each element contained in artificial mineral and the molecular weight of the artificial mineral.

$$\delta_{(i)} = \frac{N_i \mu_{CaO}}{\mu_i} \quad (5)$$

where,

δ_i – content of CaO in *i*-mineral, relative units;
N_i – number of CaO molecules in each artifical mineral, units;
μ_{CaO} – molecular weight of CaO, kg/mole;
μ_i – molecular weight of each artificial mineral, contained in a clinker, kg/mole.

The methodology for estimating CO_2 emissions from the calcination process in Ukraine's cement sector is reviewed in [19] for general cases when enterprises' technological regulations are not available. The inventory of CO_2 emissions based on the data from the enterprises' technological regulations is shown in Table 1.

Table 1. CO_2 emission factor by types of cement produced in Ukraine, 2001

Name of cement		Clinker content in cement, relative units	Artificial mineral in clinker	Mineralo-gical composition of clinker (% of weight)	CaO content in clinker, (%)	CO_2 emission factor, t CO_2/t cement[1]
Sort	Sub-types					
Cement for common construction purposes	Portland cement	0.9649	$3CaO \cdot SiO_2$	40-65	0.6567	0.5223
			$2CaO \cdot SiO_2$	15-40		
			$3CaO \cdot Al_2O_3$	5-15		
			$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	10-20		
	Portland cement with blended	0.7691	$3CaO \cdot SiO_2$	40-65	0.6556	0.4156
			$2CaO \cdot SiO_2$	15-40		
			$3CaO \cdot Al_2O_3$	5-15		
			$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	10-20		

[1] The factor for estimation of CO_2 emissions from the technology process at cement production (t CO_2/t cement) takes into consideration a correction for the CKD factor (1.05) and the ratio of the molecular weight of CO_2 and CaO (0.785). The process for deriving this factor estimation is described in section 4.2.

Name of cement		Clinker content in cement, relative units	Artificial mineral in clinker	Mineralo-gical composition of clinker (% of weight)	CaO content in clinker, (%)	CO_2 emission factor, t CO_2/t cement[1]
Sort	Sub-types					
	Cement for asbestos cement products	0.9581	$3CaO \cdot SiO_2$	40-65	0.6655	0.5256
			$2CaO \cdot SiO_2$	15-40		
			$3CaO \cdot Al_2O_3$	5-15		
			$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	10-20		
	Fast-hardening cement	0.8205	$3CaO \cdot SiO_2 + 3CaO \cdot Al_2O_3$	0-65	0.6745	0.4562
			$2CaO \cdot SiO_2 + 4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	35		
	Highway cement	0.8150	$3CaO \cdot SiO_2$	40-65	0.6565	0.4410
			$2CaO \cdot SiO_2$	15-40		
			$3CaO \cdot Al_2O_3$	5-15		
			$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	10-20		
	Slag Portland cement	0.4628	$3CaO \cdot SiO_2$	40-65	0.6666	0.2543
			$2CaO \cdot SiO_2$	15-40		
			$3CaO \cdot Al_2O_3$	5-15		
			$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	10-20		
	Cement types for cementation without forming	0.96	$3CaO \cdot SiO_2$	40-65	0.6567	0.5196
			$2CaO \cdot SiO_2$	15-40		
			$3CaO \cdot Al_2O_3$	5-15		
			$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	10-20		
Sulfate-resistant cements	Sulfate-resistant Portland cement	0.4402	$3CaO \cdot SiO_2$	0-50	0.667	0.2420
			$3CaO \cdot AI_2O_3$	0-5		
			$3CaO \cdot AI_2O_3 + 4CaO \cdot AI_2O_3 \cdot Fe_2O_3$	0-22		
			Al_2O_3	5		
			MgO	5		
	Sulfate-resistant Slag Portland cement	0.6575	$3CaO \cdot SiO_2$	Not standard	0.6504	0.3525
			$3CaO \cdot AI_2O_3$	8		
			$3CaO \cdot AI_2O_3 + 4CaO \cdot AI_2O_3 \cdot Fe_2O_3$	Not standard		
			Al_2O_3	5		
			MgO	5		
Oil-well Portl. Cem.	Oil-well Portland cement without additives	1	$3CaO \cdot SiO_2$	Not standard	0.6655	0.5486
			$3CaO \cdot Al_2O_3$	3		
			$3CaO \cdot Al_2O_3 + 4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	22		
Alumina cement	Alumina cement	1	$CaO \cdot AI_2O_3$, $12CaO \cdot 7AI_2O_3$, $CaO \cdot 2AI_2O_3$, $2CaO \cdot AI_2O_3 \cdot SiO_2$, FeO		0.3	0.247
	Gypsum and alumina expanding cement	0.65	$CaO \cdot AI_2O_3$, $12CaO \cdot 7AI_2O_3$, $CaO \cdot 2AI_2O_3$, $2CaO \cdot AI_2O_3 \cdot SiO_2$, FeO		0.656	0.3515

3.2.2. GHG inventory estimation factors for fuel combusted for high-temperature calcination

In addition to the CO_2 released during calcination, natural gas, coal and coke are combusted for high-temperature baking during clinker production. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are released when these fuels are combusted. This section presents adaptation of the GHG inventory methodology for the high-temperatures required for calcination [1].

Calculations of GHG emissions from fuel combustion by fuel types are started with conversion of coal-equivalent units into TJ. Fuel combusted for the high-temperature calcination process in the cement sector is presented in the Ukrainian statistical forms in tons of coal-equivalent (t.c.e). To convert these data into TJ, conversion factor 29.309 (1000 t.c.e/TJ) is used.

Table 2 presents IPCC [1] carbon (C) emission estimation factors for fuels combusted in the cement sector of Ukraine in 2001. The next stage is to make corrections for the unoxidised carbon. Results of this operation are multiplied by the factor 44/12 to convert GHG emissions into CO_2-equivalent.

Table 2. Carbon emission estimation factors

Fuel	Factors	
	Carbon emissions from fuel combustion, t C/TJ	Correction for unoxidised carbon
Natural gas	14.96	0.995
Coal	26.2	0.98
Coke	29.5	0.98

Table 3 presents the IPCC [1] methane and nitrous oxide emission estimation factors for fuel combusted. To estimate methane (CH_4) and nitrous oxide (N_2O) emissions, the amount of combusted fuel in TJ should be multiplied by the relevant factors presented in Table 3.

Table 3. Methane and nitrous oxide emission estimation factors

Fuel	GHG estimation factor, kg/TJ	
	methane (CH_4)	nitrous oxide (N_2O)
Natural gas	5	0.1
Coal	10	1.4
Coke	10	1.4

Methane and nitrous oxide emissions (kg/TJ) were converted into CO_2-equivalent (Gg) using the factors 21×10^{-6} and 310×10^{-6}, respectively.

3.3. Preparation of input data

3.3.1. Background

Cement production and fuel combustion for 2001 based on data from forms 1-p and 11-MTP are shown in Table 4.

Table 4. Total cement production and fuel combustion from forms 1-p and 11-MTP, 2001

Statistical forms	Administrative unit	Cement production, thousand tonnes	Specific fuel combustion, kg c.e./tonne	Fuel combustion, t.c.e.
				Total
1-P	Autonomous Republic of Crimea	281.1	Data not available (-)	-
	Dnipropetrovsk oblast	1,385.4	-	-
	Donetsk oblast	668.2	-	-
	Ivano-Frankivsk oblast	532.1	-	-
	Lugansk oblast	1.6	-	-
	Lviv oblast	544.0	-	-
	Mykolayiv oblast	232.4	-	-
	Odessa oblast	165.4	-	-
	Rivne oblast	484.2	-	-
	Kharkiv oblast	605.9	-	-
	Khmelnitsky oblast	821.0	-	-
	City of Kyiv	65.0	-	-
	Ukraine	5,786.3	-	-
11-MTP	Autonomous Republic of Crimea	165.06	255.8	42,223
	Dnipropetrovsk oblast	1,378.49	98.8	136,195
	Donetsk oblast*	605.80	163.2	98,867
	Ivano-Frankivsk oblast	417.56	236.4	98,711
	Lugansk oblast	-	-	-
	Lviv oblast	544.00	186.2	101,292
	Mykolayiv oblast	232.39	156.1	36,276
	Odessa oblast	161.59	194.3	31,396
	Rivne oblast	484.22	235.9	114,228
	Kharkiv oblast	605.82	259.4	157,151
	Khmelnitsky oblast	820.88	211.1	173,287
	City of Kyiv	-	-	-
	Ukraine**	5,416.67	182.7	989,626

Note: *274 t.c.e of coal is included in the total amount of fuel combusted in the cement sector of Donetsk oblast.

** 274 t.c.e of coal and 8 t.c.e of metallurgical coal is included in the total amount of fuel combusted in Ukraine's cement sector.

There is an obvious inconsistency in the data between the two forms for cement production in Crimea, Donetsk and Ivano-Frankivsk oblasts. Data for Lugansk oblast and Kyiv are not provided in form 11-MTP. The inconsistency is mainly explained by the delay in the submittal of the two forms by the sector's enterprises. It is recommended that the cement production be drawn from form 1-p, which is used for the official statistics [20].

3.3.2. Preparation of input data on cement production quantities

The quantities of cement produced in 2001 by administrative units of Ukraine by type are shown in Table 5. In general when the information contained in enterprises' technological regulations are not available in order to apply formulas 1 and 4, it is necessary to have information on the mineralogical composition of the clinker and the clinker content of the cement to determine the lime (CaO) content in each cement type. In this case, information on the cement mix is taken from DSTU [5,6,8]. In our situation, estimations were made based on the data on mineralogical and compositional components of the cements taken from the technological regulations of separate enterprises (Table 1).

Table 5. Cement production by type in 2001, thousand tonnes

Administrative unit	Cement for common construction purposes,							Sulfate-resistant cements		Oil-well Portland cement	Alumina cement		Total
	Portland cement	Portland cement with blended	Cement for asbestos cement products	Fast-hardening cement	Highway cement	Slag Portland cement	Cement types for cementatio without forming	Sulfate-resistant Portland cement	Sulfate-resistant Slag Portland cement	Oil-well Portland cement without additives	Alumina cement	Gypsum and alumina expanding cement	
Autonomous Republic of Crimea	0	26.9	0	0	0	254.2	0	0	0	0	0	0	281.1
Dnipropetrovsk oblast	0	1,015.3	0	0	0	331.6	7.2	0	31.3	0	0	0	1,385.4
Donetsk oblast	0	161.3	107.2	0	0	386.6	0	13.1	0	0	0	0	668.2
Ivano-Frankivsk oblast	0	277.6	254.5	0	0	0	0	0	0	0	0	0	532.1
Lugansk oblast	1.6	0	0	0	0	0	0	0	0	0	0	0	1.6
Lviv oblast	0	526.5	0	0	17.5	0	0	0	0	0	0	0	544.0
Mykolayiv oblast	0	191.4	0	0	0	27	0	0	14	0	0	0	232.4
Odessa oblast	0	165.4	0	0	0	0	0	0	0	0	0	0	165.4
Rivne oblast	0	338.5	100.6	0	0	0	0	0	0	45.1	0	0	484.2
Kharkiv oblast	96.5	154.8	66.6	77.2	0	208.6	0	0	1.7	0	0.4	0.1	605.9
Khmelnitsky oblast	168	647.5	0	0	0	0	0	1.2	0	4.3	0	0	821.0
City of Kyiv	65	0	0	0	0	0	0	0	0	0	0	0	65.0
Ukraine	331.1	3,505.2	528.9	77.2	17.5	1,208	7.2	14.3	47	49.4	0.4	0.1	5,786.3

3.3.3. Preparing input data on fuel combustion for maintaining high-temperature calcination process.

Fuel combusted per unit of cement produced at the Oblast (administrative unit) for the high-temperature calcination process is calculated by combining the production data from form 1-p, used for available statistics, and form 11-MTP, which contains total fuel combusted for cement production at the administrative units' level. The proposed method is based on the formula:

$$E_r = b_r V_r , \qquad (6)$$

where:

E_r – calculated fuel combustion by administrative unit (t c.e.);
r – index of administrative unit;
b_r – specific fuel combustion by administrative unit, kg c. e./tonne (from 11-MTP form);
V_r – cement production, thousand tonnes (from 1-p form).

In cases where fuel consumption data obtained according to the formula (6) and the data from form 11-MTP differs by more than 2%, it is proposed to define the fuel consumed based on the weighted average specific consumption for cement production for either the dry or wet technology according to the formula:

$$E_r = b_r^* V_r , \qquad (7)$$

where:

E_r – calculated fuel combustion by administrative unit (t c.e.);
r – index of administrative unit;
b_r^* – average weighted specific fuel consumption under one technology (dry or wet) by administrative units of Ukraine, kg.f.c./tonnes (11 MTP form)
V_r – cement production, thousand tonnes (from 1-p form);

The specific fuel combustion data from form 11-MTP and the data estimated by formula 6 are shown in Figure 1.

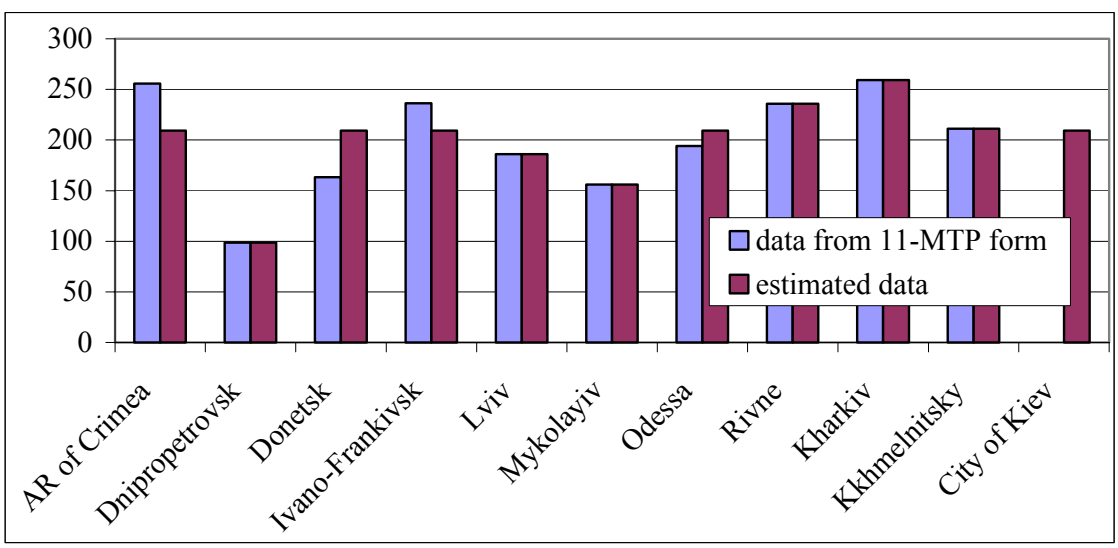

Figure 1. Specific fuel combustion for cement production in the cement sector of Ukraine in 2001 p. (kg c.e./tonne)

This figure shows that the data from form 11-MTP for specific fuel combustion in Crimea, Donetsk and Ivano-Frankivsk regions are significantly higher than the estimated values. The estimated values and data from the 11-MTP form are practically identical for other regions.

Data for the specific fuel combustion provided in Table 6 contains data contains the calculated data for all administrative units of Ukraine, except Crimea, Donetsk, and Ivano-Frankivsk, where the corrected data from equations 6 and 7 was used.

Table 6. Total quantities of cement production and fuel combustion in 2001 assumed for estimation of GHG emissions in Ukraine cement sector

Administrative unit	Cement production, thousand tonnes	Specific fuel consumption per product (operation) unit, kg c.e./tonne	Fuel consumption, t.c.e.
			Total
Dry technology of cement production			
Dnipropetrovsk oblast	1,385.4	98.8	136,877.52
Total for Ukraine (dry technology)	1,385.4	98.8	136,877.52
Wet technology			
Autonomous Republic of Crimea	281.1	209.31	58,837.04
Donetsk oblast*	668.2	209.31	139,860.94
Ivano-Frankivsk oblast	532.1	209.31	111,373.85
Lugansk oblast	1.6	209.31	334.90
Lviv oblast	544	186.20	101,292.80
Mykolayiv oblast	232.4	156.10	36,277.64
Odessa oblast	165.4	209.31	34,619.87
Rivne oblast	484.2	235.90	114,222.78
Kharkiv oblast	605.9	259.40	157,170.46
Khmelnitsky oblast	821	211.10	173,313.10
City of Kyiv	65.0	209.31	13,605.15
Total for Ukraine (wet technology)**	4,400.9	213.8	940,916.53
Total for Ukraine**	5,786.3	186.3	1,077,794.05

Note: *274 t.c.e of coal is included in the total amount of fuel combusted in the cement sector of Donetsk oblast.

** 8 t.c.e of metallurgical coal is included in the total amount of fuel combusted in Ukraine's cement sector.

Based on the analysis of Table 6 we may make thëëëe conclusion, that the estimated quantity of total fuel combusted in the calcination process exceeds the total value in form MTP-11 (Table 4) by 8.2%. Major differences are in the for Donetsk region by 29.3% higher than the MTP-11 value, 28.2% for the Autonomous Republic of Crimea, and 11.4% for Ivano-Frankivsk region.

4. GHG inventory

4.1. Technological processes of calcination

The CO_2 emissions calculated for the calcination process based on the data in Tables 1 and formula (1) are presented in Table 7.

Table 7. CO_2 emissions from technological processes of calcination in the cement sector of Ukraine in 2001, Gg

Administrative unit	Cement for common construction purposes,							Sulfate-resistant cements		Oil-well Portland cement	Alumina cement		Total
	Portland cement	Portland cement with blended	Cement for asbestos cement products	Fast-hardening cement	Highway cement	Slag Portland cement	Cement types for cementation without forming	Sulfate-resistant Portland cement	Sulfate-resistant Slag Portland cement	Oil-well Portland cement without additives	Alumina cement	Gypsum and alumina expanding cement	
Autonomous Republic of Crimea	0	9.17	0	0	0	41.26	0	0	0	0	0	0	50.43
Dnipropetrovsk oblast	0	372.29	0	0	0	82.08	3.68	0	10.67	0	0	0	468.72
Donetsk oblast	0	64.13	56.38	0	0	111.96	0	3.17	0	0	0	0	235.64
Ivano-Frankivsk oblast	0	119.97	131.93	0	0	0	0	0	0	0	0	0	251.90
Lugansk oblast	0.82	0	0	0	0	0	0	0	0	0	0	0	0.82
Lviv oblast	0	230.06	0	0	3.86	0	0	0	0	0	0	0	233.92
Mykolayiv oblast	0	83.32	0	0	0	7.35	0	0	5.24	0	0	0	95.91
Odessa oblast	0	76.60	0	0	0	0	0	0	0	0	0	0	76.60
Rivne oblast	0	157.83	53.53	0	0	0	0	0	0	21.28	0	0	232.64
Kharkiv oblast	51.88	64.18	36.10	35.22	0	57.21	0	0	0.64	0	0.10	0.04	245.37
Khmelnitsky oblast	85.25	312.38	0	0	0	0	0	0.29	0	2.03	0	0	399.95
City of Kyiv	34.94	0	0	0	0	0	0	0	0	0	0	0	34.94
Ukraine	172.89	1,489.93	277.94	35.22	3.86	299.86	3.68	3.46	16.55	23.31	0.10	0.04	2,326.84

4.2.Estimating uncertainty of an inventory of greenhouse gases emissions from the calcination technology process

To estimate CO_2 emissions from the technology process at cement production, it is necessary to estimate the clinker content in each cement type and the CaO content in the clinker [19]. The ranges of the CaO content presented in the technological regulations of the enterprises indicate that the range of the clinker component in the cement varies from 0% to 63% and from 0% to 5% for lime (CaO) content in the clinker.

The lack of data on the clinker and CaO components contents creates uncertainty in the estimation of CO_2 emissions from the calcination process. This requires an estimate of uncertainty (or actual accuracy [2]) of the CO_2 emissions, which is based on the uncertainty of the initial data.

The estimate of uncertainty in the initial data is based on a function of the probability density distribution [2]. This approach is applied for discrete random quantities that could be set by a list of all probable values and their probabilities [21]. These lists include possible values of the components, which may be determined based on the technological regulations of the cement enterprises. The probabilities are estimated by creating a separate matrix of the quantities of cement produced by type with the specific content of clinker in the cement and CaO content in the clinker. The obtained result is an estimate of the clinker content in the cement and CaO in the clinker.

The standard deviation is calculated for each of the average values (factors of component contents) to the uncertainty of the CO_2 emissions inventory from the calcination process for specific cement types and for Ukraine's cement sector as a whole. The uncertainty of the initial data is estimated based on the uncertainty for the inventory of CO_2 emissions from the calcination process for each cement type. The estimate of uncertainty of the initial data is calculated by:

$$U_i = \sqrt{\left(\frac{\sigma_{kl}}{M_{kl}}\right)^2 + \left(\frac{\sigma_{CaO}}{M_{CaO}}\right)^2} \times 100\%, \qquad (8)$$

where:

U_i – uncertainty of initial data for inventory of CO_2 emissions from the calcination process for i cement type (% of the mathematical expectation of the clinker content in the i cement type and lime (CaO) content in the clinker);
i – cement type
σ_{kl}, σ_{CaO} – standard deviation of the clinker content in the cement and the lime (CaO) content in the clinker;
M_{kl}, M_{CaO} – expected average of the clinker content in the cement and the lime (CaO) content in the clinker;

The total uncertainty of CO_2 emissions from the calcination process for cement production in Ukraine is estimated as the average from all emission as follows [2, 21]:

$$U_{total} = \frac{\sqrt{\sum (U_i V_i)^2}}{\sum V_i}, \qquad (9)$$

where: U_{total} – uncertainty of an initial data of an inventory of CO_2 emissions from the technology process in the cement sector of Ukraine (half the 95% confidence interval divided by the total and expressed as a percentage), %;
i – cement type;
V_i – emissions CO_2 from the technology process for i cement type, Gg;
U_i – uncertainty of initial data for inventory of CO_2 emissions from the calcination process for i cement type, %.

Table 8 contains the uncertainty estimates based on the range of data for the clinker content in cement and CaO content in the clinker using formula 8 for the cement types and Ukraine's administrative units and for the cement types and for Ukraine as a whole.

Table 8. Estimated uncertainty of CO_2 emissions by cement type

Administrative unit	Cement for common construction purposes,							Sulfate-resistant cements		Oil-well Portland cement	Alumina cement		Total
	Portland cement	Portland cement with blended	Cement for asbestos cement products	Fast-hardening cement	Highway cement	Slag Portland cement	Cement types for cementatio without forming	Sulfate-resistant Portland cement	Sulfate-resistant Slag Portland cement	Oil-well Portland cement without additives	Alumina cement	Gypsum and alumina expanding cement	
Autonomous Republic of Crimea	0	0.560	0	0	0	22.784	0	0	0	0	0	0	18.640
Dnipropetrovsk oblast	0	8.033	0	0	0	2.221	0	0	0.696	0	0	0	6.392
Donetsk oblast	0	13.752	1.570	0	0	6.914	0.560	2.271	0	0	0	0	4.994
Ivano-Frankivsk oblast	0	5.053	0.302	0	0	0	0	0	0	0	0	0	2.412
Lugansk oblast	0.696	0	0	0	0	0	0	0	0	0	0	0	0.696
Lviv oblast	0	5.577	0	0	0.722	0	0	0	0	0	0	0	5.485
Mykolayiv oblast	0	12.362	0	0	0	0.151	0	0	0.784	0	0	0	10.739
Odessa oblast	0	0.151	0	0	0	0	0	0	0	0	0	0	0.151
Rivne oblast	0	0.526	0.526	0	0	0	0	0	0	0.526	0	0	0.380
Kharkiv oblast	0.526	8.671	0.841	2.526	0	8.110	0	0	0.304	0	0	0	2.980
Khmelnitsky oblast	1.052	1.315	0	0	0	0	0	2.271	0	0.526	0	0	1.052
City of Kyiv	0.526	0	0	0	0	0	0	0	0	0	0	0	0.526
Ukraine	0.553	2.446	0.380	0.526	0.722	4.388	0.560	2.089	0.513	0.482	0	0	1.667

This calculation provides that the uncertainty of the inventory of CO_2 emissions from the calcination process is 1.667%. Estimated uncertainty values contained in Table 8 are directly dependence on the range of the values on the clinker content in the cement and CaO content in the clinker from the technology modes of the enterprises.

4.3. Fuel combustion to provide high-temperature conditions of calcination

The GHG emissions from fuel combusted to provide the high temperatures necessary for calcination are based on the data in Table 6 and equations (2) and (3). The emissions shown in Table 9 are for the three types of GHG emissions (CO_2, CH_4, and N_2O) and in CO_2 equivalent.

Table 9. Quantity of GHG emissions from fuel combustion to provide high-temperature conditions for calcination, 2001

Administrative unit	GHG emissions			
	CO_2-eq., Gg	CO_2, Gg	CH_4, Mg	N_2O, Mg
AR Crimea	94.35	94.12	8.62	0.17
Dnipropetrovsk oblastoblast	219.50	218.96	20.06	0.40
Donetsk oblast*	224.60	224.03	20.53	0.42
Ivano-Frankivsk oblast	178.60	178.16	16.32	0.33
Lugansk oblast	0.54	0.54	0.05	0.00
Lviv oblast	162.44	162.03	14.84	0.30
Mykolayiv oblast	58.18	58.03	5.32	0.11
Odessa oblast	55.52	55.38	5.07	0.10
Rivne oblast	183.17	182.72	16.74	0.33
Kharkiv oblast	252.05	251.42	23.03	0.46
Khmelnytsky oblast	227.93	277.24	25.40	0.51
City of Kyiv	21.82	21.76	1.99	0.04
Ukraine**	1,728.72	1,724.42	157.99	3.17

Note: *274 t.c.e of coal is included in the total amount of fuel combusted in the cement sector of Donetsk oblast;
** 8 t.c.e of metallurgical coal is included in the total amount of fuel combusted in Ukraine's cement sector.

This shows that, in terms of CO_2-equivalent, over 99% of total emissions of the nearly 1.7 million tonnes are directly from CO_2 and less than 1% are from CH_4, and N_2O.

4.4. Combined GHG emissions in the cement sector

Combined GHG emissions in the cement sector are calculated as the sum of emissions from the calcinations process and from fuel combusted to provide the high temperatures for the calcination process. Table 10 provides the estimated total GHG emissions in Ukraine's cement sector by administrative units.

Table 10. Quantity of GHG emissions in Ukraine's cement sector, 2001, Gg

Administrative unit	GHG emissions		
	from the calcination process, CO_2, Gg	from fuel combustion, CO_2-eq., Gg	combined, CO_2-eq., Gg
AR Crimea	50.44	94.35	144.79
Dnipropetrovsk	468.72	219.50	688.22

oblastoblast			
Donetsk oblast*	235.64	224.60	460.24
Ivano-Frankivsk oblast	251.90	178.60	430.50
Lugansk oblast	0.82	0.54	1.36
Lviv oblast	233.92	162.44	396.36
Mykolayiv oblast	95.92	58.18	154.10
Odessa oblast	76.60	55.52	132.12
Rivne oblast	232.64	183.17	415.81
Kharkiv oblast	245.36	252.05	497.41
Khmelnytsky oblast	399.95	227.93	627.88
City of Kyiv	34.94	21.82	56.76
Ukraine**	2,326.85	1,728.72	4,055.57

Note: *274 t.c.e of coal is included in the total amount of fuel combusted in the cement sector of Donetsk oblast;
** 8 t.c.e of metallurgical coal is included in the total amount of fuel combusted in Ukraine's cement sector.

Analysis of the data from Table 10 shows that technology CO2 emissions from the calcination process account for more than 57% of the total GHG emissions in Ukraine's cement sector.

4.5. Potential for GHG emissions reduction under the condition of switching to the dry technology for cement production

Switching to the dry process for producing cement would increase the energy needed for crushing and grinding the raw materials, but reduce fuel consumed to provide the high temperatures needed for the calcination process, for a net reduction in energy consumed for cement production. An estimate of the energy savings and emissions reduction potential can be obtained by comparing the fuel consumed by the two types of processes. Since only fuel consumed for the calcination process is available and not for the preparation of the mineral inputs, the estimates of energy savings and emissions reduction are the maximum achievable.

The dry process, used only in the Dnipropetrovsk region, has significantly lower specific fuel consumption that the other regions, ranging from 34 – 62% of the consumption for the wet technology used in the other Oblasts, and 50% of the average for the wet technology for Ukraine. The estimated potential reduction in fuel use and emissions for switching Ukraine's cement production entirely to the dry technology is shown in Table 11.

Table 11. Potential for reducing GHG emissions by switching the production of cement in Ukraine to the dry process

Administrative unit	Designed volumes of fuel combustion in 200 for the wet production process. t.c.e.	Designed volumes of fuel combustion in 2001 for the dry production process. t.c.e.	Potential for reduction of fuel combustion. t.c.e.	Potential for GHG emissions reduction (CO_2-eq. Gg)
AR Crimea	58,837.04	27,772.68	31,064.36	49.82
Donetsk oblast*	139,860.94	66,018.16	73,842.78	118.74
Ivano-Frankivsk oblast	111,373.85	52,571.48	58,802.37	94.30
Lugansk oblast	334.90	158.08	176.82	0.33
Lviv oblast	101,292.80	53,747.20	47,545.60	76.22
Mykolayiv oblast	36,277.64	22,961.12	13,316.52	21.36
Odessa oblast	34,619.87	16,341.52	18,278.35	29.36

Rivne oblast	114,222.78	47,838.96	66,383.82	106.48
Kharkiv oblast	157,170.46	59,862.92	97,307.54	156.04
Khmelnytsky	173,313.10	81,114.80	92,198.30	147.77
City of Kyiv	13,605.15	6,422.00	7,183.15	11.51
Ukraine**	940,916.53	434,816.92	506,107.61	811.95

Note: *274 t.c.e of coal is included in the total amount of fuel combusted in the cement sector of Donetsk oblast;

** 8 t.c.e of metallurgical coal is included in the total amount of fuel combusted in Ukraine's cement sector.

The estimates in Table 10 show that potential reductions in fuel consumption of about 506,107.61 t.c.e. or about 47% from the 2001 level. The corresponding decrease in emissions of about 811,950.4 tonnes in CO_2 equivalent is nearly 47% of the level of emissions from energy consumption in 2001, and about 20% of the combined emissions from calcination and energy consumption.

Conclusions

1. 13 types of cement were produced in Ukraine in 2001 with a total amount of 5,786.3 thousand tonnes.
2. Over 60% of the cement is produced in four Oblasts - Dnipropetrovsk at 1,385.4 thousand tonnes, Khmelnytsky at 821 thousand tonnes, Donetsk at 668.2 thousand tones, and Kharkiv at 605.9 thousand tonnes.
3. The two sources of GHG emissions are 1) the calcination of material inputs that generates CO_2 emissions and 2) fuel consumption needed to provide the high temperatures for calcinations generates CO_2, CH_4, and N_2O.
4. The report applies a methodology developed to calculate GHG emissions for cement production in Ukraine that is adapted to Ukrainian conditions and available data.
5. DSTU established the content of clinker in cement and content of CaO in clinker. But, the ranges in the values established by DSTU are wide, which introduces a high level of uncertainty in the inventories based on these values. Therefore, to improve the accuracy of CO_2 emissions from the technology process it is better to use the technological regulations of some enterprises.
6. Based on the data from the specific enterprises' technological regulations, CO_2 emissions were developed for the calcination process and expressed in tonne of CO_2 per tonne of cement. These were highest for Oil-well Portland cement without additives – 0.5486; for Cement for asbestos cement products – 0.5256; and for Portland cement – 0.5223, which has the highest lime (CaO) content.
7. Production data was drawn from forms 1-p as official statistics are based on data from this form.
8. The volumes of fuel consumed for calcination were drawn from form 11-MTP. In cases where there was disagreement between production data from forms 1-p and 11-MTP, the fuel consumption data were adjusted. The adjusted data provide a conservative (low) assessment of the GHG emissions.
9. Estimations show that GHG emissions from the calcination process total 2.3 million tonnes of CO_2-equivalent plus 1.7 million tonnes of CO_2-equivalent from fuel consumption, for a total of 4.0 million tonnes of CO_2-equivalent.
10. ARENA-ECO performed estimation of uncertainty of the initial data of technology modes of separate enterprises for performing GHG inventory by administrative units and cement types. The uncertainty value for the cement sector of Ukraine as a whole equals 1.667%. The estimated values of uncertainties directly depend on variations in the data on clinker content in the cement and lime (CaO) content in the clinker from the technology modes of the enterprises.
11. The potential for reducing cement sector GHG emissions by switching from the "wet" to "dry" production technology would provide a reduction of nearly 811 thousand tonnes of CO_2-equivalent, which is over 20% of total CO2 emissions.

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