

POLISH PERSPECTIVE ON PROCESS EMISSIONS IN THE STEEL SECTOR

Segmentation of greenhouse gas emission into fuel combustion emissions and process emissions is very important in energy-intensive industries, including the steel sector. The ratio of process emissions to emissions from fuel combustion is different in various industries, e.g. in the cement industry is 60:40 (no data for the steel sector).

A common feature of all energy-intensive industries are very limited opportunities to reduce process emissions. Most often, this would require the development of entirely new processes. Another solution could be the method of capturing and storage carbon dioxide underground (CCS), but for various reasons, including social, this technology does not develop too intensively towards the creation of practical possibilities of its use.

Therefore, it seems advisable to accurately separate process emissions and fuel combustion emissions in each production process of energy intensive industries and to make efforts so that these emissions are excluded from the EU Emissions Trading Scheme (ETS). Currently, benchmarks set by the European Commission define the total emission cap, and the share of emissions from the combustion of fuels is determined based on gas combustion, which further deteriorates the competitiveness of these industries, the functioning of which is based on the combustion of coal, as the steel sector in Poland.

In many manufacturing processes reactions of carbon with oxygen are triggered not in order to produce energy required in the process (fuel emission), but are the result of chemical reactions necessary to obtain the required physico-chemical semi-finished products or products (process emissions) – e.g. calcium carbonate decomposition during sintering of iron ore.

The paper presents the results of analyses that are fundamental to making efforts to exclude process emissions from the EU ETS and cover the identification of the issue and the justification for exclusion. In the steel sector, the most promising in this area are the following processes: sintering, blast furnace, BOF and steel melting in an electric arc furnace. Other energy-intensive industries, such as industrial energy, heating, non-ferrous metals, chemicals, cement, glass and lime, also conducts similar analyses, and the consolidated results will be the subject of a request to the European Commission.

Keywords: process emissions, greenhouse gases, sintering, blast furnace, basic oxygen furnace BOF, electric arc furnace EAF

POLSKI POGLĄD NA EMISJE PROCESOWE W SEKTORZE STALOWYM

Podział emisji gazów cieplarnianych na emisje ze spalania paliw i emisje procesowe jest bardzo ważny w energochłonnych gałęziach przemysłu, w tym w sektorze stalowym. Stosunek emisji procesowych do emisji ze spalania paliw jest różna w różnych gałęziach przemysłu, np. w przemyśle cementowym wynosi 60:40 (brak danych dla sektora stalowego).

Wspólną cechą wszystkich energochłonnych gałęzi przemysłu są bardzo ograniczone możliwości redukcji emisji procesowych. Najczęściej wymagałoby to opracowania zupełnie nowych technologii. Innym rozwiązaniem mogłaby być metoda wychwytywania i składowania dwutlenku węgla pod ziemią (CCS), ale z różnych powodów, w tym społecznych, ta technologia nie rozwija się zbyt intensywnie w kierunku stworzenia praktycznych możliwości jej wykorzystania.

Dlatego też wydaje się wskazane dokładne rozdzielanie emisji procesowych i emisji ze spalania paliwa w każdym procesie produkcji w energochłonnych gałęziach przemysłu i podejmowania działań na rzecz wyłączenia tych emisji z systemu handlu uprawnieniami do emisji (tzw. ETS). Obecnie kryteria określone przez Komisję Europejską określają całkowity limit emisji, a udział emisji ze spalania paliw jest ustalany w oparciu o spalanie gazu, co dodatkowo pogarsza konkurencyjność tych gałęzi przemysłu, których funkcjonowanie opiera się na spalaniu węgla, jak sektor stalowy w Polsce.

W wielu procesach produkcyjnych reakcje węgla z tlenem są przeprowadzane nie w celu wytworzenia energii potrzebnej w procesie (emisje ze spalania paliw), ale są wynikiem reakcji chemicznych niezbędnych do uzyskania półproduktów lub produktów o określonych wymaganiach fizyko-chemicznych (emisje procesowe) – np. rozkład węglanu wapnia podczas spiekania rudy żelaza.

W artykule przedstawiono wyniki analiz, które mają fundamentalne znaczenie dla dołożenia starań, aby wykluczyć emisje procesowe z EU ETS, pokazać skalę zagadnienia i uzasadnić to wyłączenie. W sektorze stalowym, najbardziej obiecujące w tym obszarze są procesy: spiekania, wielkopiecowy, konwertorowy i topienia stali w piecu elektrycznym. Inne energochłonne gałęzie przemysłu również prowadzą podobne analizy, a skonsolidowane wyniki tych analiz będą przedmiotem wniosku do Komisji Europejskiej.

Słowa kluczowe: emisje procesowe, gazy cieplarniane, spiekanie, wielki piec, konwertor tlenowy, łukowy piec elektryczny

1. INTRODUCTION

The climate and energy package constitutes a set of legislative documents (directives and decisions), which implement mechanisms aimed at achieving ambitious goals of the EU in terms of greenhouse gases' emission reduction, increase in renewable energy sources share in consumption of final energy, and increase in energy consumption efficiency.

One of the mechanisms of the climate and energy package implementation is a concept of low-emission economy, which, for example, in Poland is realised by the establishment of the National Programme for Development of Low-Emission Economy, which is currently under public consultation.

The main ways to achieve low-emission economy are the following:

- reduction in greenhouse gases emission,
- improvement of energy efficiency,
- increase in share of renewable energy sources and increase in the share of bio-fuels,
- use of CO₂ technology – Carbon Capture and Storage (CCS) and, in view of the increasing social resistance towards that method – use of the technology of Carbon Capture and Recycling (CCR) or Carbon Capture and Utilisation (CCU).

The European Emission Trading System (ETS) has been launched in 2005 and covers over 11 thousand installations in the energy sector and industry in the EU and Norway, which (as the largest emitters), are responsible for almost half of the EU carbon dioxide emission. Approximately 750 installations in Poland are covered by the system.

The present trading period, lasting from 2013–2020, differs significantly from two previous ones. In this period, EU ETS is based on directive 2009/29/EC (altering directive 2003/87/EC). Its main goal is to meet auctioning commitments provided for in the climate and energy package, i.e. reduction in emission of greenhouse gases by 21% as compared to 2005 emission level. The scope of the system was extended with new activities (industry branches) and gases. One general European emission limit was introduced, which replaced the previous national limits used in preceding periods. On annual basis, the said limit is reduced by 1.74% of the number of allowances issued on average by Member States in the period 2008–2012 [1].

The following have also been implemented:

- a principle of auctioning emission allowances by Member States,
- gradual departure from free allocation to installation,
- „emission benchmark” conditioning the amount of free permits for the given product.

The condition to obtain a set of free allowances is analysis of the risk of production transfer outside EU (carbon leakage risk). Risk analysis covers several aspects, including [2]:

- Cost aspect – ratio of indirect and direct cost of production (stemming from directive implementation) to gross added value – it has to reach at least 5%,
- Trade intensity – ratio of the value of EU imports/exports (to and from third countries) to EU market volume – the value of intra-community trade and imports needs to exceed 10%,

- Meeting any of the above criteria at the level of 30%.

The remaining economy branches accounting for 60% of greenhouse gases emission, which are not subject to EU ETS, shall be bound by provisions of the second key document, which is a non-ETS decision. The said decision assumes the target of 10% reduction in emission of greenhouse gases in the entire EU, in sectors such as: transportation, agriculture, and construction. Under non-ETS, the EU reduction target was differentiated and some of the less prosperous member countries may even increase their emission in the period 2013–2020. Pursuant to these provisions, Poland is able to increase its emission in the non-ETS sector by 14%, as compared to 2005 [3].

In light of the above, the Polish industry has been placed in an exceptionally difficult situation due to the fact that the Polish power sector is a coal based industry. Moreover, process emission and emissions from industrial power engineering have been included in Emission Trade System (ETS).

A discussion was launched amongst industry managers and technology engineers, and clear actions have been taken to change some provisions of the binding directives. The next directive is under preparation.

In order to ensure systematic growth of competitiveness of Polish enterprises in new conditions, as well as to increase competitiveness of actions taken on behalf and in the interest of its members, a forum of branch commercial organizations was created, named FORUM^{CO₂} [4]. It deals with issues stemming from EU directive No. 2003/87/EC.

Since 27th May, 2014, FORUM^{CO₂} has been implementing the project **“Process emissions – actions in favour of ETS exclusion”**, aimed at developing joint strategy, documents and taking up actions to exclude process emissions from ETS in the period 2020–2030 [5].

The definition of “process emission” itself evoked numerous discussions among technology engineers and lawyers. Process emission benchmarks constitute another serious issue. These two issues: definition of process emissions and the said emission benchmarks for:

- iron ore sintering (in other words: sintered ore),
- blast furnace process (blast furnace hot metal),
- converter process (liquid converter steel),
- rolling value for the three items above (in other words: for an integrated steel plant or liquid metal in form of steel produced from hot metal in oxygen converter),
- steelmaking electrical process in EAF (liquid electrical steel)

are subject to deliberation in the present paper, the goal of which is to define process emissions, i.e. those that are free (gratuitous), at the aforesaid stages of steel production, as well as proper justification thereof.

2. DEFINITION OF PROCESS EMISSION

The basis for analyses is the definition of “process emission” provided for in the Regulation of the EU Commission No. 601/2012, Art. 3 Definitions, item. 30 [6]:

“process emissions” mean greenhouse gas emissions other than combustion emissions occurring as a result of intentional and unintentional reactions between substances or their transformation, including the chemical or electrolytic reduction of metal ores, the thermal decomposition of substances, and the formation of substances for use as product or feedstock.”

This definition does not refer neither to stoichiometric ratios of reactions taking place in particular technological processes nor to the necessary excess of reducer vs. values indicated by stoichiometry, so that the chemical process might be fully completed.

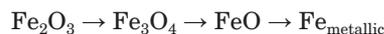
In the reality of advanced technological processes, also those classified as the best available (BAT), there is no thermodynamic balance, which means that processes do not take place with 100% efficiency. In the case of reduction, including iron oxides, excess of reducer is necessary vs. the value implied by stoichiometry [7]. Without the said excess, reduction process will not take place to the required extent. Therefore, unavoidable emission of reduction gases has to be higher than as implied by stoichiometry. Reaction of reduction of Fe_2O_3 to FeO and FeO to metallic Fe in blast furnace process requires significant excess of a reducer. The said excess is $n = 100 : \text{CO}_2$, where CO_2 means the concentration of CO_2 in the system in the state of equilibrium at the specified temperature. For example, at the temperature of 700°C , the ratio of excess n required for reduction of FeO is $100 : 40 = 2.5$, and at the temperature of 1000°C – $100 : 25 = 4.0$. The ratio determines how many times more CO needs to be introduced to the system vs. the volume of CO determined by stoichiometric equation of reduction reaction.

In practice, one aims at maximising the efficiency of technological processes, however at present one needs to refer to the level of the best of these, and not the theoretical, but the perfect ones.

Moreover, numerous reactions, including reactions of reduction and decomposition, taking place in metallurgical processes require heat, as they are endothermic. Therefore, at least a part of heat generated during a technological process is required for the process reaction to take place. Moreover, in case of a wide range of the existing technologies, deemed to be the best available, heat from combustion of solid fuels cannot be replaced by another heat source without the replacement of the entire technology with a completely different one (which is inefficient at present). In other words, heat obtained from combustion of solid and/or gas fuels, or at least a part thereof, is also “process and unavoidable” and as such it should be recognised.

The group of technologies includes processes of sintering and the blast furnace process. Combustion of solid fuels in these processes is a source of the required heat, which cannot be introduced by any other way (e.g. by means of heating with the use of electricity generated in water, wind or solar power plants, i.e. without emission of CO_2), and simultaneously reduction gas. Reduction process, including the reduction of iron oxides, apart from the reducer, requires a properly elevated temperature and time. Thus, e.g. heat in sintering process should mainly lead to melting complex oxide phases for the purpose of obtaining agglomerate. Solid fuel cannot be eliminated from the said process, to be replaced with another energy source. Moreover, processes of reduction of higher iron oxides to lower

oxides take place during ore sintering: hematite is reduced to magnetite and partly to wustite:



Due to short impact time of temperatures at which the reduction takes place, as well as suction of significant volumes of air by the sintered layer, reduction in this process is limited.

Taking into account the aforesaid arguments, it is justified to emphasise the part of definition which says that “process emissions are those emissions than cannot be avoided” whilst this may not be limited to emission of CO_2 from reduction and decomposition.

The definition must take into account all possible emissions that meet the criteria, i.e. which are emissions that cannot be avoided or reduced in a manner different than reduction in production level. These emissions should be listed in details in the form of an attachment.

Due to the fact that the Directive and definitions presented therein aim at imposing reduction in emission of greenhouse gases, also the modified or new definition of process emission has to take into account the unavoidable emissions, but to a justified extent. The lowest emissions possible presently, generated as a result of optimisation of the process in terms of emission of CO_2 , are postulated as justified. Simultaneously, one cannot forget that though multiple discussions are devoted to sustainable development, i.e. preference of no-emission technologies, optimisation from the perspective of production cost in relation to achievement of the proper quality of product is still of a crucial meaning. Lost cost competition means elimination from the market.

It seems that the only justified issue that may or should be considered in the case of processes threatened by transfer to non-EU countries as a result of excessive increases in the cost of production in case of the necessity to purchase emission allowances – it is not the segregation of emission into process and non-process, but definition of the justified volume of emission (or energy consumption volume and related greenhouse gases emission) for the given technology. Nevertheless, it will not be easy, as it should take into account local (national, regional) specificity, including available sources of raw materials and energy.

In the contemporary steel industry of EU countries (and globally), a limited number of processes (technologies) of iron and steel manufacturing deemed to be the best available production methods exists. These are described in a reference BAT document [8]. There is, however a significant variability of:

- charge conditions in particular countries, which fundamentally impacts emission level,
- access to electricity from power plants that do not emit CO_2 .

Due to the fact that coal plays a double role, acting as reducing agent and energy carrier-fuel, it is important for the volume of carbon from coke burning to not be double-counted, if it had been previously counted elsewhere. Coke and other fuels used as reducing agents during production of iron and steel should be deemed as production process emissions, and not as fuels used for energy purposes. During production of iron and steel, the largest source of CO_2 emission is the use of reducing agent (coal or coke), which accounts for ca.

90% of the whole emission of CO₂ from technological processes.

To sum up the above deliberations, the authors of this study propose the following definition of process emission, which should obtain 100% free (gratuitous) allowances:

Process emissions that are unavoidable are those emissions of greenhouse gases from technological processes covered with the present directive, stemming from stoichiometric ratios of technological process reactions with justified reducer excess, which are not the emissions of greenhouse gases generated during exothermal reaction of fuel with oxygen, conducted for energy generation purposes.

3. ESTIMATION OF PROCESS EMISSIONS FROM THE PROCESSES OF IRON AND STEEL PRODUCTION

As it was mentioned before, process emissions compliant with the proposed definition were estimated in the paper for the following processes: iron ore sintering, blast furnace, as well as converter and electric steel melting. According to the document prepared for the needs of the European Commission for 2012 [9], the issue in 27 EU countries concerns the following numbers of operating steel plants:

| | |
|--------------------------|-----|
| – sinter plants | 50 |
| – blast furnaces | 88 |
| – converter steel plants | 41 |
| – electrical steel shops | 232 |

3.1. PROCESS EMISSIONS IN IRON ORE SINTERING

Sources of CO₂ emissions in iron ore sintering are the following:

- charge materials, including: ores, waste in the form of dust, sludge, scales,
- combustion of gases in ignition furnaces,
- combustion of coke breeze (and/or anthracite),
- decomposition of carbonates (lime and dolomite) introduced as fluxes.

The above emissions are called “direct emissions”. In balances of emission, also indirect emissions are taken into account, i.e. emissions generated by suppliers of charge materials such as steelmaking lime or calcined dolomite, as well as emissions related to the production of electricity used by sinter belt drives, fans, and other necessary sinter plant equipment. Only then one may consider the emission as total (direct + indirect).

Both in the balance of carbon in sintering process and in the balance of emission, one takes into account coal that is contained in the product as well as in by-products, where part of coal introduced into the process is bounded, as well as recovery of heat of sinter or exhaust gases which reduce CO₂ emissions.

According to analyses of German researchers, who analysed data from three modern integrated steel plants [10], the volume of total emission of CO₂ from iron ore sintering process ranges from 314 to 377 kg of CO₂ per tonne of finished sinter. Structure of the emission is the following:

| | |
|----------------------------|-------|
| – combustion of solid fuel | 60.0% |
|----------------------------|-------|

- decomposition of lime stone and emissions from production of burnt lime 22.0%
- decomposition of carbonates 11.0%
- electricity (emission at its producers) 4.3%
- combustion of gas in ignition furnaces 2.7%

Taking into account the proposed definition, process emissions from sinter belt for Polish conditions account for 36% of the entire emission volume. Emissions from combustion of carbon contained in solid fuel and in gas used to ignite the mix are deemed to be non-process emissions [11].

3.2. PROCESS EMISSIONS IN BLAST FURNACE PROCESS

The sources of CO₂ in the blast furnace process are:

- coke and secondary fuels,
- coal introduced with iron-bearing charge,
- fluxes (calcium and magnesium carbonates).

The balance of CO₂ is influenced by the consumption of reducer and structure of charge. Various charge conditions, e.g. use of sinter, raw ores, iron pellets, lead to variations in the emission of CO₂. Volume of emission stems from the difference in the volume of carbon introduced to the process in the form of raw materials and fuels, and released along with products such as pig iron, granulated slag, blast furnace gas. The share of CO₂ emission from reducer (coke plus secondary fuels) is the most significant and ranges from 1600 to 1800 kg CO₂/t of hot metal depending on type of charge material [10].

CO₂ emission related to direct reduction of iron oxides for blast furnace in Polish conditions was calculated from thermal and material balance according to Ramm. It amounts to 373 kg CO₂/t of hot metal.

The calculation of process emissions of CO₂ related to indirect reduction of iron oxides was conducted as per authors' methodology, comprising calculations of emission of CO₂ during reduction of hematite, wustite, silicone and manganese transferred to hot metal. Process emission of CO₂ estimates as per the said methodology ranges from 671÷847 kg CO₂/t of hot metal, i.e. constitutes 51.5 to 60% of the total direct emissions of CO₂. The applied technology, on one hand, does not take into account the reduction with carbon of other iron compounds (ferrites, silicates, sulfides), as well as reduction with hydrogen.

3.3. PROCESS EMISSIONS IN CONVERTER STEELMAKING

In converter process the source of CO₂ emission are charge materials containing carbon, or calcium or magnesium carbonates introduced to the process. These include:

- blast furnace hot metal,
- scrap: home scrap, amortization scrap and skulls,
- raw slagforming materials (in form of carbonates),
- carbonaceous energy materials.

The main source of CO₂ in converter process is the necessary technological operation consisting in refining of carbon introduced with charge material. The volume of carbon that needs to be removed by oxidation from metal bath, and as a corollary to be bounded in form of process CO₂, may be defined from the balance of carbon in converter process.

In determination of the balance of carbon, and thus the volume of CO₂ emission from converter process, approximate data from domestic converter steel plants were adopted. For the said data, the volume of process emission from carbon oxidation in metallic charge, i.e. from metal bath refining, was estimated in the range of 127.6÷187.9 kg CO₂/t of steel. Additionally, production of 1 tonne of steel results in the generation of process emission in the range from 46 to 60 kg CO₂/t of steel on account of decomposition of carbonates contained in slagforming materials. An amount of 173 up to 250 kg CO₂ per 1 tonne of manufactured steel is generated in converter process. This means that practically the entire emission of CO₂ in converter process is a process emission, not related to combustion of fuels introduced to the process.

3.4. PROCESS EMISSIONS IN ELECTRICAL STEEL MELTING

Total emission of CO₂ related to manufacturing of steel in EAF includes direct and indirect emissions. Indirect emissions are related to the generation of electricity used in EAF, as well as emissions related to the production of burnt lime and burnt dolomite, used as slagforming additives.

Direct emissions in the steelmaking electrical process (arc furnaces) are comprised of emissions from carbon contained in charge materials (scrap and alloying elements), intentionally added to the charge for the purpose of bath refining as a result of air refining of the required volume of coal injected to slag in the point of contact with metal bath for the purpose of slag foaming, to deoxidise the slag, introduced in gas firing the burners, from use of carbon electrodes and afterburning of the generated CO to CO₂. Process emissions include all the above except for those generated as a result of combustion of gas in oxy-gas burners and use of carbon electrodes.

Due to the complementarity of furnaces and ladle treatment equipment used for manufacturing of steel in electrical steel shop, one should take into consideration the sum of used energy, slagforming and technological additives, as well as the sum of the generated emissions, including CO₂ emissions.

Taking into account only direct emissions from EAF for Polish electrical steel plants, the share of process emissions ranges from ~88.2% to ~89.5% (on average ~89%).

4. SUMMARY

Internal estimates of the volumes of process emissions related to the production of blast furnace sinter, blast furnace hot metal, as well as converter and electrical steel were developed.

In the process of iron ore sintering, only those emissions which are related to decomposition of carbonates were deemed process emissions, while the entirety of emissions related to combustion of solid fuel and gas used for mix ignition was deemed non-process. The authors of the study did so, despite their opinion that heat generated from combustion of carbon in sintering process is entirely process heat (it cannot be supplied to sinter ore in any other way). Moreover, a part of the generated CO plays a role of a reducer, however due to the complexity of the process, the concerned volume cannot be defined. It is estimated that process emissions account for ca. 36% of CO₂ emissions from this type of installation.

In the case of blast furnace process, the authors considered process emissions as emissions which stem from direct and indirect reduction of iron oxides. In the case of reduction of iron oxides, the excess of reducer is required vs. the value indicated by stoichiometry. Without the said excess, the reduction process will not take place to the required extent. Therefore, unavoidable emissions of reduction gases have to be higher than those implied by stoichiometry. Reaction of reduction of Fe₂O₃ to FeO and FeO to metallic Fe requires a significant excess of the reducer. It is estimated that process emissions, depending on the conditions of blast furnace operations, account for 51.5 to 65% of CO₂ from the said installation.

It should be emphasised that among experts, there are some who think that only emissions, which are related to generation of heat from throat gas used for firing of stoves or other purposes in blast furnaces should be deemed non-process. This item is a pure energy yield of the process (excess heat), not related to the technological demand for pig iron smelting. Other components of thermal balance of blast furnace are in the nature of things related to the course of physical, chemical and physico-chemical phenomena and transitions of the components of charge, required in completion of the process of hot metal production. Similarly, the whole heat generated in the process of ore sintering might be considered process emission.

On the other hand, in the case of the converter process, 100% of CO₂ emissions were considered as process emissions, as it stems from intended action consisting

Table 1. Volume and share of process and non-process emissions of CO₂, and values for rolling emission for converter steel – internal (own) estimates

Tabela 1. Wielkość i udział procesowych i nieprocesowych emisji bezpośrednich CO₂, oraz wartości dla emisji ciągniętej dla stali konwertorowej – szacunki własne

| Product | Process emission | | Non-process emission | |
|--|----------------------------------|----------|-------------------------------|----------|
| | kg CO ₂ /t of product | Share, % | kg CO ₂ /t product | Share, % |
| Blast furnace sinter | 75 | 36 | 135 | 64 |
| Blast furnace hot metal | 671–847 | 51.5–65 | 632–456 | 48.5–35 |
| Converter steel | 173–250 | 100 | 0 | 0 |
| Converter steel (rolling emission: sinter plant + blast furnace + converter steel) | 954–1208 | 53–65 | 838–661 | 47–35 |
| Electrical steel | 73–84 | 88–89 | 10 | 12–11 |

in the removal of carbon from metal bath through oxygen refining.

In the case of electrical process, ca. 89% of CO₂ emissions were deemed process emissions, as it stems from intended action consisting in the removal of carbon from metal bath and oxidation of carbon electrodes.

– Table 1 presents the summary of the results of the conducted analyses concerning process emissions, i.e. unavoidable emissions, for which the manufacturers should receive 100% free emission permits.

The analysis of data presented in the above table implies that the share of unavoidable emissions for an integrated steel plant ranges from 53÷65%.

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