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CLIMATE CHANGE MITIGATION SCENARIOS FOR THE UKRAINIAN STEEL SECTOR BASED ON BEST AVAILABLE TECHNOLOGIES DEPLOYMENT*

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Abstract

The plausible scenarios for steel production and consumption and prospects for reducing greenhouse gas emissions by implementing the best available technologies (*BAT*) in the steel industry of Ukraine towards 2030 are studied. It is shown that the introduction of *BAT* can reduce specific CO_2 emissions by 25%. Taking into account the possible dynamics of *BAT* implementation, only in the absence of growth in steel production a reduction in the average annual CO_2 emissions can be ensured. With a moderate growth of steel production, the introduction of *BAT* enables stabilization of total emissions at about the current level. Under conditions of accelerated growth of steel production, total CO_2 emissions increase even with the introduction of *BAT*. The results of study show that in order to meet Ukraine's international commitments under the Paris Climate Agreement, the introduction of innovative ironmaking and steelmaking technologies with greater, compared to *BAT*, CO_2 reduction potential should begin after 2027.

Keywords: best available technologies, carbon dioxide emissions, emission reduction, modeling, steel sector

1. Introduction

Following the global strategy for climate change mitigation, in Ukraine a system for trade of greenhouse gases (*GHG*) emissions' allowances should be implemented since 2021, therefore understanding the opportunities for reducing the emissions is extremely important for domestic industry. However, currently there is a lack of scientifically sound analysis on

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the basis of which it would be possible to choose a development strategy, in particular for the steel industry, taking into account climate commitments.

According to the United Nations’ Emissions Gap Report 2019 (UNEP, 2019), global *GHG* emissions continue to rise, reaching 55.3 Gt CO_2 eqv in 2018. By 2030, emissions would need to be 25% and 55% lower than in 2018 to put the world on the least-cost pathway to limiting global warming to below 2°C and 1.5°C respectively.

The steel industry is the largest industrial source of *GHG* emissions worldwide. In Ukraine in 2018 (the last year for which a detailed emission inventory is available at the time of writing) 20.5 million tons of pig iron, 21.0 million tons of steel, 31.7 million tons of sinter and 21.4 million tons of pellets were produced (Matukhno et al., 2019), which resulted in more than 50 million tons of *GHG* emissions (CO_2 equivalent), including emissions from the combustion of process gases for power generation. Direct *GHG* emissions occurred during the manufacture of these products comprised 39.88 million tons (Lyashenko et al., 2020).

Despite the significant excess in steel production capacity worldwide, taking into account growth in steel demand by 51% by 2050 from 2011 projected by the International Energy Agency (IEA, 2012), Ukraine can maintain its niche in world steel exports, mainly in the sector of low value-added products (today the share of ingots and semi-product in Ukrainian exports is 42% (World Steel Association, 2019)). Moreover, the estimated need to replace obsolete metal-intensive equipment in industry, infrastructure and municipal sector exceeds 330 million tons (Amosha et al., 2013), which is more than the ten years’ production output with full capacity utilization. Based on this, steel sector in Ukraine in the foreseeable future has opportunity to maintain significant volume.

According to (World Steel Association, 2018) opportunities to reduce CO_2 emissions in Ukraine through the introduction of the best available technologies (*BAT*) exceed the world average by more than twice.

The purpose of this work is to develop scenarios for reducing *GHG* emissions in the steel industry via the *BAT* deployment under conditions of different steel production and consumption development strategies’ implementation.

In the course of the research the following tasks were formulated:

- modeling the steel production and consumption scenarios for Ukraine towards 2030;
- determining the dynamics of the introduction of the *BAT* in the steel industry towards 2030;
- modeling of carbon dioxide emissions reduction pathways for steel industry under the conditions of realization of different development scenarios for production and consumption of steel with simultaneous introduction of the *BAT*.

The work consists of three parts:

- elaboration of scenarios for the development of steel production and consumption;
- analysis of prospects for the *BAT* deployment;
- modeling the carbon dioxide emissions reduction pathways for Ukraine’s steel sector towards 2030 under conditions of *BAT* deployment.

2. Material and methods

To address the objectives of the study, a model was developed to assess the feasibility of reducing energy consumption and greenhouse gas emissions through the introduction of BAT by 2030, which corresponds to the first period of implementation of the Paris Agreement.

In the model some BATs recommended in (Remus et al., 2013), is economically feasible for the steelmaking enterprises in Ukraine have been considered as follows:

- Retrofitting of sintering machines with increased roasting surface area and improved production technology. Thanks to reduction in specific consumption of various fuels including coal, natural gas, coke oven gas, coke nut, blast furnace top gas as well as owing to decrease in electricity consumption, such modernization ensures cutting the CO_2 emissions by 30.69 kg per ton of sinter.
- Reconstruction of blast furnaces with the deployment of top-pressure recovery turbines (TPRT). TPRT enables transformation of blast furnace top gas pressure into the electric energy thus avoiding excessive electricity generation with equivalent to reduction of CO_2 emissions by 30.2 kg per ton of pig iron under conditions of average power sectors emissions intensity in Ukraine.
- Upgrading the blast furnaces hot stoves. This BAT ensures reduction of the fuels (blast furnace top gas and natural gas) for production of hot blast in the stoves and reduction of coke consumption in blast furnaces resulting in cutting the CO_2 emissions by 61 kg per ton of pig iron;
- Replacing open-hearth method of steel production by less carbon intensive basic oxygen converter method. This BAT ensures substantial cutting in the consumption of natural gas, electricity, oxygen, lime and coal resulting in CO_2 emissions reduction by 354.1 kg per ton of steel.
- Substitution of ingot casting by continuous casting. This BAT substantially reduces energy consumption (natural gas, blast furnace top gas and electricity) and helps to reduce CO_2 emissions by 276 kg of ton of steel.

Listed above BATs are well proven in the steel industry over the world and, according to Energostal (Ukrainian R&D organization) (Shatokha et al., 2017), cover over 90% of the CO_2 emissions reductions potentially achievable in iron and steel industry via BAT deployment. Therefore, we omit in our analysis other, less impactful, technologies.

Energy consumption and CO_2 emissions are calculated taking into account the production output, technologies and resources used. Several complementary modernization scenarios with using BAT are developed to cost-effectively reduce CO_2 emissions and increase energy efficiency.

Our model assumes that between 2021 and 2030 the growth in steel production and consumption might be expressed using Compound Annual Growth Rate (CAGR), widely used in forecasting future values in various applications including industrial production, consumption and so on. In particular, for the steel sector CAGR was applied by Pal at al. (Pal et al., 2016) using the following equation:

$$CAGR(t_0, t_n) = \left(\frac{V(t_n)}{V(t_0)} \right)^{\frac{1}{t_n - t_0}} - 1 \qquad (1)$$

where $V(t_0)$, $V(t_n)$ - initial and final consumption, respectively; t_0, t_n - initial and final years, respectively.

The CAGR indicator is calculated via the successive iterations method based on statistics and assumptions about the volume of production and consumption in 2030. The model considers three scenarios for the production and consumption of steel shown in Table. 1. Although 1.58 million tons of steel were imported in 2018 (about 7% of the total balance of steel products) (World Steel Association, 2019), steel imports to Ukraine were taken as zero - not only to simplify the model, but also because that most of the imported items are produced or could be produced at domestic enterprises. The scenarios assume the use of various indicators of the average annual growth rate in compound percentages. The indicators of 2019 are accepted as the basic level of steel output.

Table 1. Scenarios of steel production and consumption

№	*Scenario*	*Indicators for 2030, million tons*		*CAGR, %*		*Comments*
		Production	*Consumption*	*Production*	*Consumption*	
1	Moderate production, moderate consumption	30	10	3.4	5.4	Steel consumption roughly corresponds to the level before the financial crisis of 2008
2	High production, high consumption	35	15	4.8	9.0	Steel production roughly corresponds to the level before the financial crisis of 2008
3	Moderate production, high consumption	30	15	3.4	9.0	The scenario best fits the sustainable economic development concept

Indicators of GHG emission reductions due to BAT implementation were adopted in accordance with the recommendations by Energostal (Shatokha et al., 2017). The baseline data on GHG emissions for 2018 were adopted, being the most reliable official statistics currently available. In particular, the following indicators of carbon dioxide emissions were adopted:

- in the production of pig iron in blast furnaces 1.66 tCO_2/t of hot metal (including the production of coke and sinter);
- overall, in the production of crude steel, taking into account the power generation from blast furnace top gas combustion and the limestone firing, the emissions comprise 2.38 tons of CO_2/tons of steel.

The dynamics of the BAT deployment was modeled based on the S-curve, which usually well describe the diffusion of innovations in industry (McGahan, 2000), using the following simplified equation derived from sigmoid function (de Villafranca Casas et al., 2018):

$$n_t = \frac{M}{1 + \exp\left[\frac{-\ln(81)}{\Delta t} \cdot \left(t - (t_r + \Delta t / 2\right)\right]} \tag{2}$$

where

n_t – market penetration in the current year;
M – saturation limit (maximum share of technology in the market after it becomes mainstream);
t_r – year when the rapid growth starts (our model assumes start of this phase from 10% of the saturation limit);
Δt – takeover time, specified as the time in years required for technology to grow from 10% to 90% of the market;
t – current year;
factor 81 represents the ratio of saturation thresholds (10% and 90%) calculated as (90x90)/(10x10).

Transformation of the steel production infrastructure towards 2030 is shown in Fig. 1 demonstrating the evolution of steel production in Basic Oxygen Furnaces (BOF), Open Hearth Furnaces (OHF) and Electric Arc Furnaces (EAF). Noteworthy, steel output worldwide in OHFs amounts to 0.4% with last furnaces remaining in Ukraine and Russia. Therefore, the decommissioning of OHFs in Ukraine is indispensable for aligning with global steelmaking practice. On the other hand, share of EAF over the world varies in a very wide range and is not associated with technology advancement being more dependent upon local conditions (availability of scrap, cost of electricity and so on).

A more significant reduction in CO_2 emissions could be achieved by increasing the share of steel production in the EAF, but, given that in Ukraine the steel production infrastructure is built under the "blast furnace - BOF/OHF" route, this paper does not consider this option and the EAF share is kept constant (7.5%). The following two factors also support this approach:

1) In Ukraine, there is a shortage of high quality scrap, whereas the resources of good quality iron ore are abundant. Even according to the scenarios provided in Table. 1, the demand for scrap for BOF should be 6-7 million tons per year, and with the growing share of steel production in the EAF, this need will increase significantly. In addition, a significant increase in the share of EAF will require a rather radical change in the infrastructure of steel production, which involves additional financial costs.

2) Increasing the share of steelmaking in the EAF does not correspond to the strategic scenario of modernization of steel sector of the International Energy Agency termed B2DS (IEA, 2017), aimed at limiting global warming within less than 2°C, where the strategic direction is the deployment of innovative ironmaking, which can be most effectively implemented within the modernization of the "blast furnace - BOF" production route.

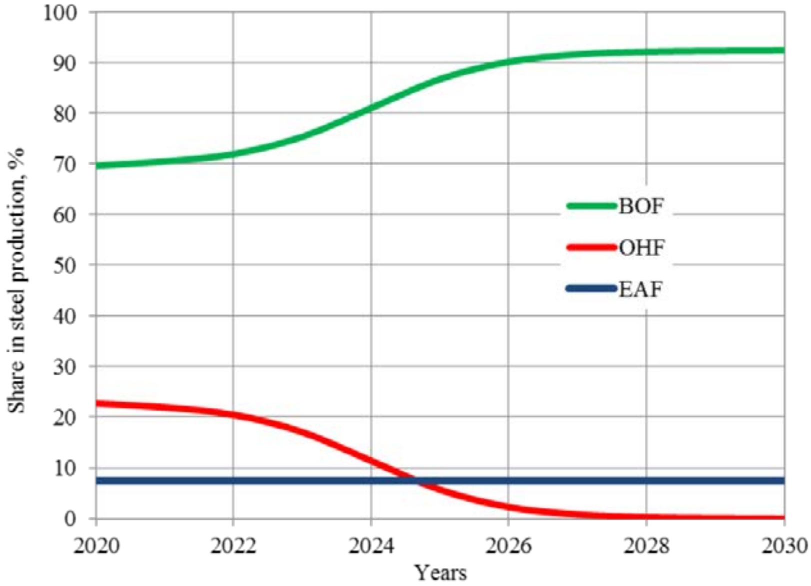


Fig. 1. Share of BOF, OHF and EAF method in steel production

Assumptions about transition in steel casting method are shown in Fig. 2. Nowadays Ukraine has the world’s highest share of ingot casting - 46%, whereas the world average is 3.6%. Many producers still keep a tiny share of ingot casting - mostly for producing large and small-batch items, therefore in this study we aim at 95% of ingot casting in 2050.

The model assumes the following assumptions about the market and features of steel production in Ukraine:

steel imports during the period studied is zero;

- 1 ton of sinter is used to produce 1 ton of pig iron, and the rest of the necessary iron ore raw material is pellets;

- to produce 1 ton of steel 0.80 tons of pig iron is used (the rest is scrap);
- initial steel production 20.8 million tons per year (as in 2019);
- initial consumption of steel 5.4 million tons per year (as in 2018).

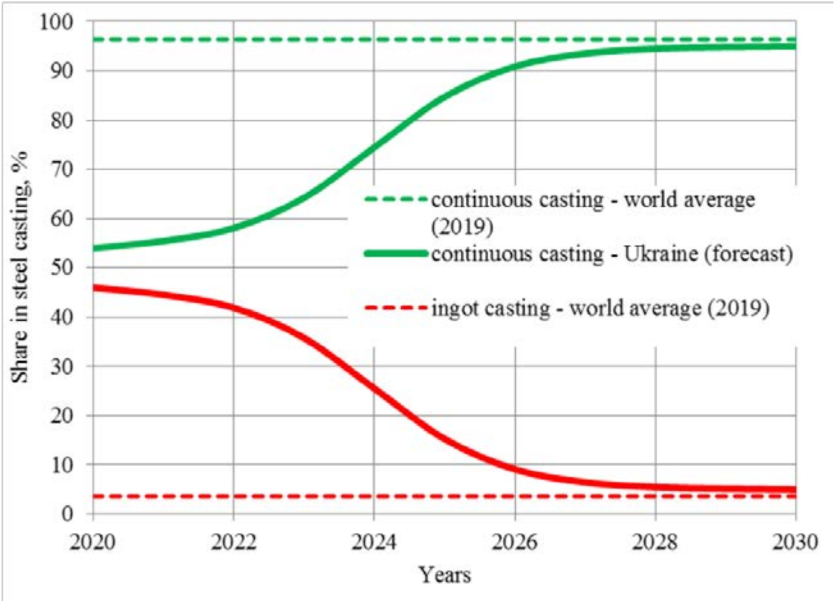


Fig. 2. Share of continuous and ingot casting in total steel output

The assumptions made in the model regarding the potential for reducing carbon dioxide emissions and the features of the introduction of the BAT are summarized in Table 2.

Table 2. Reduction of CO_2 emissions and modes of BAT implementation

№	*Best available technologies*	*Emission reductions CO_2 according to (Shatokha et al., 2017)*	*Share of production where BAT is implemented, %*		*Year of rapid growth*
			2018	*2030*	
1	Modernization of sinter plants	31 kg CO_2 /т sinter	0	100	2021
2	*TPRT* installation	30.2 kg CO_2/т cast iron	0	100	2022
3	Modernization of hot stoves	61 kg CO_2/т cast iron	0	100	2023
4	Substitution of ingot casting by continuous casting	276 kg CO_2/т steel	52.26	95	2022
5	Replacement of *OHF* with *BOF*	354.1 kg CO_2/т steel	69.3	92.5	2022

In contrast to steel production and casting methods, diffusion of other BATs considered in this study worldwide is not exhaustively reported in literature and statistical data. Calculated according to Table 2 and Eq. 2, the trajectories depicting the dynamics of these BAT's implementation in Ukraine are shown in Fig. 3.

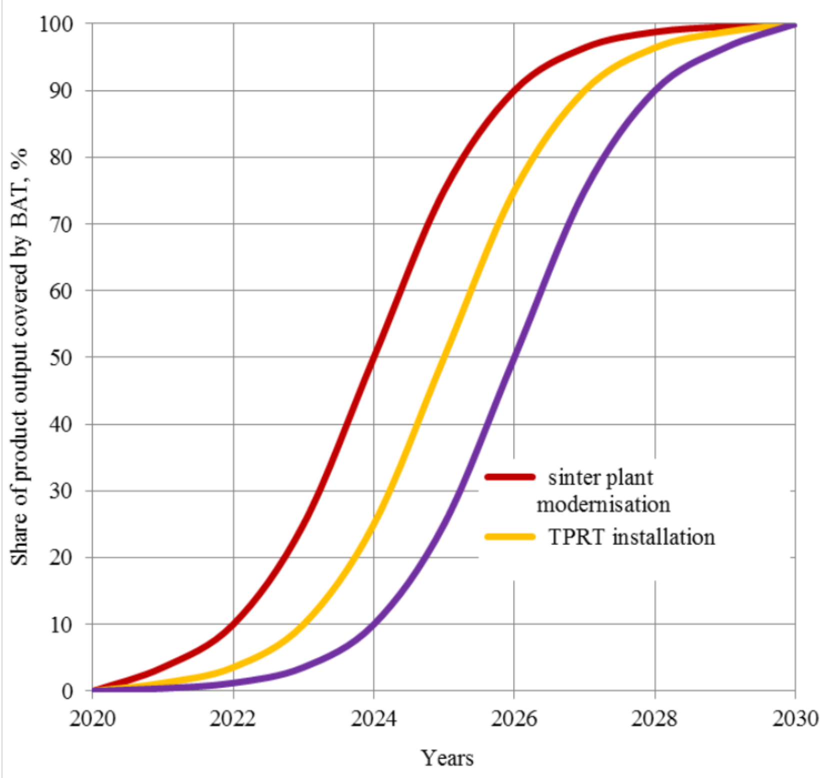
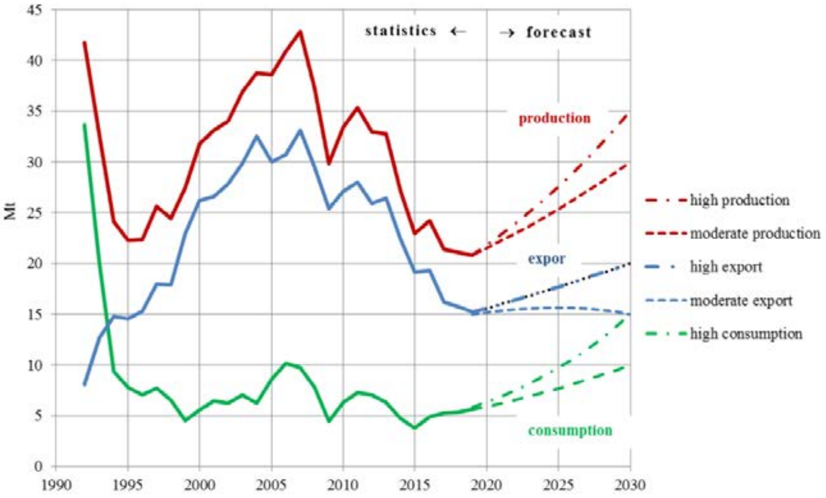


Fig. 3. Evolution of sinter plant modernization, hot stoves modernization and TPRT deployment in Ukraine towards 2030 in relationship to the share of product covered by BAT (details in Table 2)

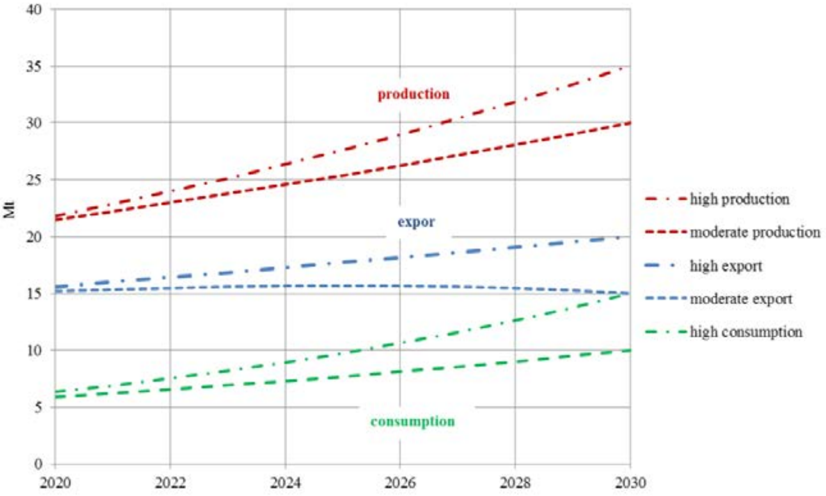
3. Resutls and discussion

Statistical data and the results of modeling the production, consumption and export of steel in three scenarios in accordance with the assumptions outlined in Table 1, are shown in Fig. 4. It is obvious that one of the preconditions for the implementation of the developed scenarios is the growth of domestic demand for steel, which corresponds to the strategic principles of socio-economic development of Ukraine. At the same time, markets for steel exports must be maintained at least at the current level.

Obtained results for the specific CO_2 emissions reduction achieved via *BAT* deployment in the Ukrainian steel sector towards 2030 are shown in Fig 5 in comparison with data for 2 °C Scenario (2DS) of the International Energy Agency towards 2050 (IEA, 2014) transformed into sectoral specific emissions in paper (Krabbe et al., 2015). 2DS offers emissions reduction pathway consistent with limiting global warming within 2 °C before the end of this century and remains basic climate change mitigation scenario of *IEA*. Although substantial emissions reduction of 25.6% is achieved the value reached in 2030 (1.77 t CO_2/t-steel), is just by 3.3% better than global average in 2017: 1.83 t CO_2/t-steel (World Steel Association, 2018) and is far above the global benchmark of 1.44 t CO_2/t-steel set by *IEA* for 2030. Although this result largely relates to obsolete current conditions of steel sector in Ukraine, the values of specific emissions above global average also indicate inevitably higher energy intensity, and correspondingly higher carbon intensity, of predominant in Ukraine primary steelmaking route based on Blast Furnace-*BOF* scheme compared with secondary steelmaking route based on Scrap-*EAF* scheme. However, the primary route shall remain an indispensable part of steelmaking throughout this century which is recognized in the *IEA* B2DS scenario (IEA, 2017) as already discussed above in Methodology section.



a)



b)

Fig. 4. Statistic data and modeling results for production, consumption and export of steel under three scenarios (million t per year): a) complete view - statistics for 1990-2019 and modeling for 2020-2030; b) detailed modeling results for 2020-2030

The results of modeling carbon dioxide emissions of Ukraine’s steel industry on the basis of different production growth scenarios (moderate and high) as well as without growth are shown in Fig. 6. Business as usual option represents case with no growth and absence of *BAT* implementation (specific emissions kept constant).

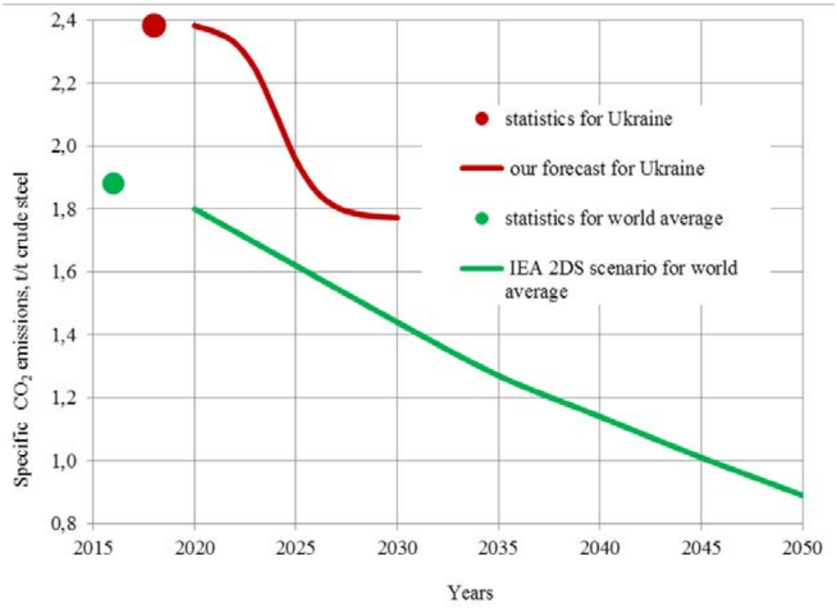


Fig.5. Statistic data and estimated reduction of specific CO_2 emissions as a result of *BAT* implementation in Ukraine's steel sector in comparison with world average and *IEA* 2°C Scenario

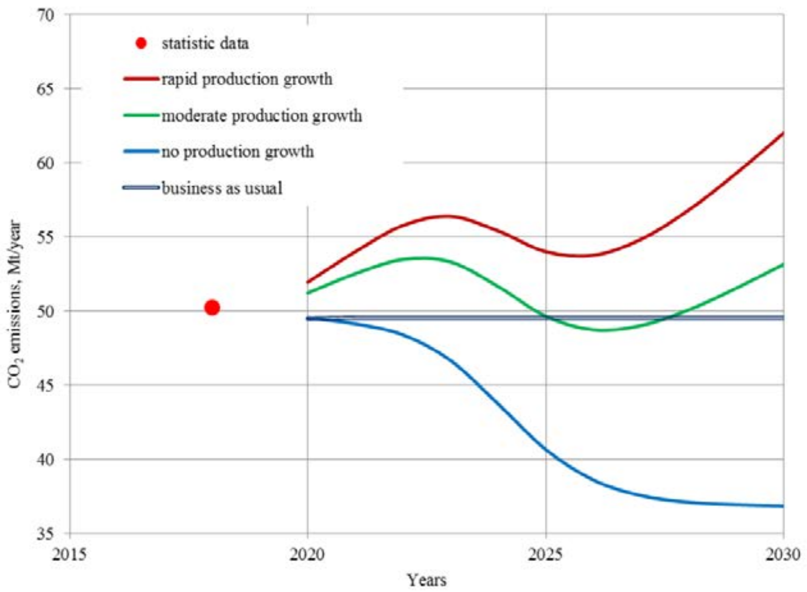


Fig. 6. The CO_2 emissions of Ukrainian steel industry during the implementation of *BAT* under conditions of different steel production scenarios

As can be seen from the data obtained from the modeling (Fig. 6), under the implementation of scenarios assuming the growth in steel production, after 2022, when the *BAT* deployment achieves maximum pace (as seen in Fig. 3) the reduction of CO_2 emissions is observed, despite the proportional annual increase in steel output (Fig. 4). In other words, decoupling of emissions from production growth is achieved, which is one of the main objectives of the Paris Agreement on Climate Change. Moreover, in the case of a moderate increase in steel production, CO_2 emissions in 2027 will even be equal to the level observed in 2018 (in general, emissions in this scenario are comparable to those for business as usual). However, after 2027, the potential for emission reductions through *BAT* is gradually exhausted, resulting in a significant increase in CO_2 emissions: for the scenario with moderate growth, emissions in 2030 will exceed the level of 2018 by 5.7%, and for the scenario with rapid growth the emissions in 2030 will exceed the level of 2018 by 23.4%.

Only for the scenario without growth of steel production there is a constant reduction of CO_2 emissions, reaching in 2030 a value of 72.2% from the 2018 level. However, this option does not correspond to the strategy of industrialized socio-economic development of Ukraine.

Modeling shows that total CO_2 emissions in the steel industry for the period of 2021-2031 will be 0.42, 0.52 and 0.57 billion m3 for scenarios without growth, with moderate and rapid growth, respectively. It should be noted that in the absence of *BAT* implementation, total emissions under the same scenarios would be 0.49, 0.62 and 0.68 billion m^3 CO_2, respectively.

Summing up, in the frames of socio-economic scenarios considering the growth of steel production, to meet Ukraine's sectoral targets and commitments under the Paris Climate Agreement, the introduction of innovative ironmaking and steelmaking technologies with greater, compared with the *BAT*, potential for reducing emissions should begin after 2027. Such technologies and prospects for their implementation worldwide have been earlier analyzed in (Shatokha, 2018). The possibilities and expected results of such technologies' application in Ukraine will be investigated in our future work.

4. Conclusions

Taking into account the need for scientifically based data for decision-making on the modernization of steel industry in Ukraine in line with international climate commitments, the scenarios of steel production and consumption coupled with the *GHG* emissions reduction via *BAT* deployment towards 2030 have been modeled. Modernization of sinter plants, modernization of blast furnace hot stoves, introduction of top gas pressure recovery turbines, substitution of open-hearth steel production with basic oxygen furnaces and replacement of ingot casting with continuous casting can provide total reduction of specific CO_2 emissions per ton of steel by 25.6%. The results of modeling show that the reduction of the average annual CO_2 emissions due to *BAT* deployment is achieved only in the absence of growth in steel production. Under conditions of moderate growth of steel production, the *BAT* deployment enables stabilization of total emissions at about the current level, and under conditions of accelerated steel production growth, total CO_2 emissions increase even if *BAT* are deployed.

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