Setting requirements to carbon intensity of thermal power plants

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Abstract. The article proposes and substantiates benchmarks of specific greenhouse gas emissions as targets to turn to more advanced and environmentally friendly production mode while reducing carbon intensity of the thermal power industry. Restrictive and stimulating levels of CO_2 emissions for thermal power plants were determined based on industry benchmarking results for different types of fuels and power stations, taking into account the actual condition of the operational equipment. Three approaches to determining carbon intensity benchmarks are considered: per ton of oil equivalent burnt (t CO_2-eq /t), per unit of generated electric energy (t CO_2-eq /MWh), and per unit of generated thermal energy (t CO_2-eq /Gcal). The study demonstrates that setting restrictive benchmarks for the use of coal in the thermal power industry would not contribute to a significant reduction of greenhouse gas emissions and slow down Best Available Techniques implementation on pulverized coal-fired thermal power plants. Therefore, the authors propose to establish carbon intensity targets taking into account both the economic and technological status of the energy sector. Additionally, the paper proposes restrictive and stimulating benchmarks for carbon intensity in electricity generation at thermal power plants to promote further reductions in greenhouse gas emissions.

1 Introduction

The achievement of the internationally approved Sustainable Development Goals (SDGs) and national development goals is not possible without an advanced energy generation sector. This is why attention of politicians, researchers and practitioners is chained to the technological, technical, economic, and environmental aspects of energy generation. On one hand, the development of modern society is impossible without reliable energy supply, and on the other, the energy sector cannot but cause a negative impact on the environment and the climate system [1]. Even when it comes to renewable energy sources, there are a number of environmental problems related to the life cycle of materials and devices used to

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generate energy. In this article, we focus on thermal power plants and approaches to the environmental, climate and technological regulation of their activities, taking into account the SDGs and national development goals.

Over recent decades, the electric and thermal energy consumption and production have demonstrated a steady growth and this trend has led to a significant environmental impact due to the rapid rise of pollutant emissions into the atmosphere, the major of such pollutants are sulphur dioxide and fuel ash (for coal-fired plants), nitrogen oxides. The greenhouse gases (GHG) emissions have grown, too [1]. Globally, more and more countries tend to regulate GHG emissions applying carbon trade related mechanisms and setting ambitions GHG targets for energy intensive industries. Accordingly, industrial enterprises strive to switch to energy sources with (at least) known and officially declared GHG emissions, and (preferably) – to lower carbon energy sources. Such a tendency becomes more and more typical for the Russian industry, too.

The national statistics for 2022 show that in the Russian Federation, total GHG emissions reached 2,042 million tons of CO_2-equivalent (CO_2-eq.), with carbon dioxide (CO_2) covering a lion's share of nearly 1,659 million tons of CO_2-eq. It is well-known, that the thermal power sector is the predominant source of GHG emissions, contributing 1,613 million tons of CO_2-eq., or 79% of the total Russian industrial GHG emissions. The emission "leaders" responsible for 87.2% of all energy-related CO_2-eq. emissions definitely are the power plants using fossil fuels of various types and grades as primary source for energy generation (1,406 million tons of CO_2-eq.) [2].

In order to achieve the national goals for GHG emission reduction in the thermal power industry, the Russian Government has established and promoted various initiatives and strategies, including fostering cleaner fuel utilization technologies, enhancing emission reduction in coal-fired power generation by implementing more energy and resource efficient fuel combustion methods, combined-cycle power plant development and startup, and by analyzing the potential rewards stemming from extensive use of the shared cogeneration of thermal and electrical energy [3-4]. The main driver for technological modernization, continual phasing form less efficient technologies to more economically and environmentally sound lies in the gradual implementation of the Best Available Techniques (BAT) [5].

According to the international approaches to the GHG emissions assessment [6], CO_2 is the only greenhouse gas that should be considered while making calculations for thermal power plants; other GHGs emitted in negligibly small quantities. This is why both in the official reporting documents and in the research articles, carbon intensity of power generation at thermal plants is represented in tons of CO_2 (rather than in tons of CO_2 equivalent) per unit of production [4, 6-7].

Globally, as well as in Russia, the decarbonization of industry and development of energy transition programs and plans are becoming more and more pressing issues [8]. This study aims to determine the values of carbon intensity benchmarks, which can serve as targets for achieving carbon neutrality in the Russian thermal power industry. This goal assumes the adoption of technologies that help to reduce the carbon footprint through a complete transition to BAT. From the economic point of view, the importance of carbon footprint reduction in the power generation sector by 2050 is specifically addressed in the Russian national strategy of socio-economic development with low greenhouse gas emissions. Finally, nowadays energy intensive industries aiming to export their products to countries planning to introduce (or already introducing) measures similar to the Carbon Border Adjustment Mechanism (CBAM) need to consider CO_2 emissions associated with the energy consumed. The same trend has become evident worldwide among largest resource-intensive economies. Chinese and Indian (since 2014 and 2024, respectively) regulators are currently implementing national programs on GHG-emission reduction and supervising various carbon trading schemes with a focus on energy-generating facilities and energy intensive industrial sectors including combustion of various fuel types with the purpose of heat and electrical power generation, aluminum production, cement industry, iron and steel production, pulp and paper production, petrochemical processess and fertilizer production. Since energy (and carbon) intensive companies are the main exporters of fertilizers, natural gas, various oils and metals to those countries, the necessity of the establishment of carbon intensity indicators for the key industrial sectors becomes more and more evident.

2 Materials and methods

The term “Indicative Carbon Intensity Parameter (ICIP)” for emission intensity benchmarks is used to emphasize the distinction between BAT-associated environmental performance levels (BAT-AELs) and reference (orienting) points which are meant to encourage production carbon intensity reduction rather than impose mandatory limits [9-10]. According to the requirements of the national standard GOST R 113.00.30-2023, this study establishes ICIP values for Russian thermal power plants using the sector benchmarking approach [9].

The ICIP approach was proposed and further developed in Russia within the framework of the transition to Best Available Techniques or so-called BAT-based regulation reform. Though nowadays carbon intensity benchmarks are set in various countries and regions, and benchmarks established in the European Union (EU) within the framework of the EU Emissions Trading System are considered not only in Europe, but also in China, India, Kazakhstan, Brazil and South Africa, there are no reports on running benchmarking of CO_2 emissions in the BAT-related Technical Working Groups.

The study uses ICIP for assessment of BAT-AELs for the key types of Russian fuels and thermal power plants and subsequently for the assessment of carbon intensity of various technologies and strategies and for the establishment of more effective GHG emission management approaches.

This process involves a quantitative assessment of specific GHG emissions (expressed in tons of CO_2-eq. per unit of heat or electrical energy produced). The study presents an analysis for various Russian fuel types and grades including various coals, natural gases and liquid oils and their application in steam turbine plants (STP), combined-cycle power plants (CCTP) and gas turbine plants (GTP).

3 Results

Following the definition of GHG benchmarking established by [9], this study considered three approaches for setting carbon intensity benchmarks: how many tons of CO_2-eq. emitted (1) per ton of oil equivalent combusted for energy generation purposes (t CO_2/toe), (2) per the amount of electrical energy (t CO_2/MWh), and (3) thermal energy (t CO_2/Gcal) generated as a result of combusting various types of fuel.

Figure 1 illustrates the carbon intensity (per ton of oil equivalent combusted) for the widely spread energy coal grades in Russia. For bituminous coals, the carbon intensity ranges from 2.597 to 2.908 t CO_2/t, while for lignite, it is higher, ranging from 2.784 to 3.229 t CO_2/t. This difference can be explained by chemical properties of various fuels, when larger amount of lignite has to be combusted to receive the same amount energy produced by lesser amount of bituminous coal. The Figure 1 shows that the carbon intensity values for all types of energy coals fall within a relatively narrow range, differing by only 20%. Introducing restrictive ICIPs for the use of certain types of coal could disrupt the current fuel supply structure for pulverized coal-fired thermal power plants without significantly reducing GHG emissions [11]. However, keeping in mind an urgent need to drive the national energy sector into low-carbon trend, it seems logical to phase out coal grades characterized by relatively high carbon content and low energy. This shift will primarily affect newly commissioned thermal power plants.

Obviously, while considering a new coal grade for a certain power plant, the decision-maker should take into account not only greenhouse gases but key BAT-AELs: fuel ash, nitrogen oxides and sulphur dioxide. In all jurisdictions, altering fuel to reduce emissions of pollutants is an approach categorized as a BAT [5]. As far as GHG emissions are concerned, researchers focus rather on turning from coal to natural gas than going into details of solid (or liquid) fuel properties. Nevertheless, in all cases, to decrease emissions, preference should be given to higher-calorific coals.

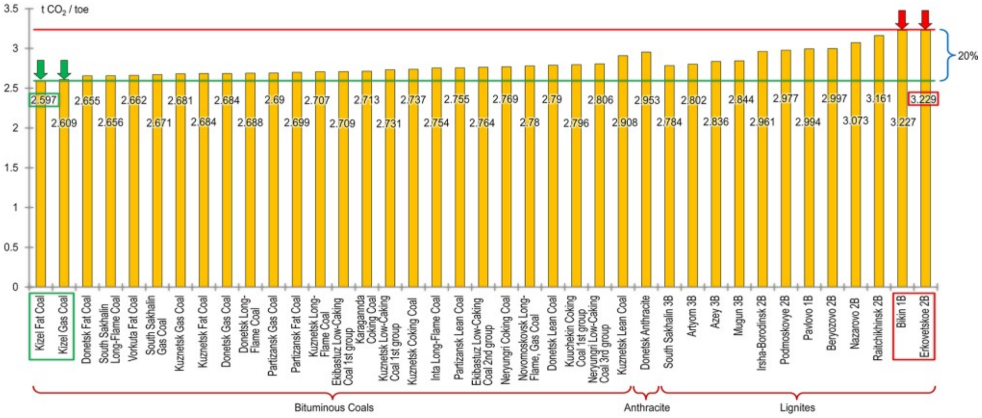

Fig. 1. Carbon intensity (per ton of oil equivalent): Russian energy coals.

In order to receive more reliable data on the carbon intensity of various energy-generating techniques applied, this study performs a quantitatively assessment of CO_2-eq. emissions per unit of electrical (t CO_2/MWh) and thermal (t CO_2/Gcal) energy generated at Russian thermal power plants. The analysis included various fuel types and power plant technologies operating at subcritical (SubC), supercritical (SC), and ultra-supercritical (USC) parameters.

The carbon intensity of electricity generation technologies (t CO_2/MWh) was computed taking into the account the power station type (condensing power plants versus combined heat and power plants) and the efficiency of STPs, GTPs, and CCGT power plants using different organic fuels (Figure 2).

The electrical efficiency values used in the calculations were derived from data obtained while reviewing the Reference Document on Best Available Techniques (BREF) for Large Combustion Plans [4]. It is necessary to emphasize that the review procedure was initiated especially to establish indicative carbon intensity parameters for the sector regulated using the concept of BAT. Along with the review of the BREF for Large Combustion Plants, reviews of similar documents for energy intensive industries are conducted. Thus, decision-makers can see the overall picture and understand the barriers for exporting carbon (and energy) intensive products to be overcome in the nearest future, and which sector and inter-sectoral BAT should be considered to decrease GHG emissions.

Additional information used to prepare the article was collected during the surveys of Russian thermal power plants conducted by the authors.

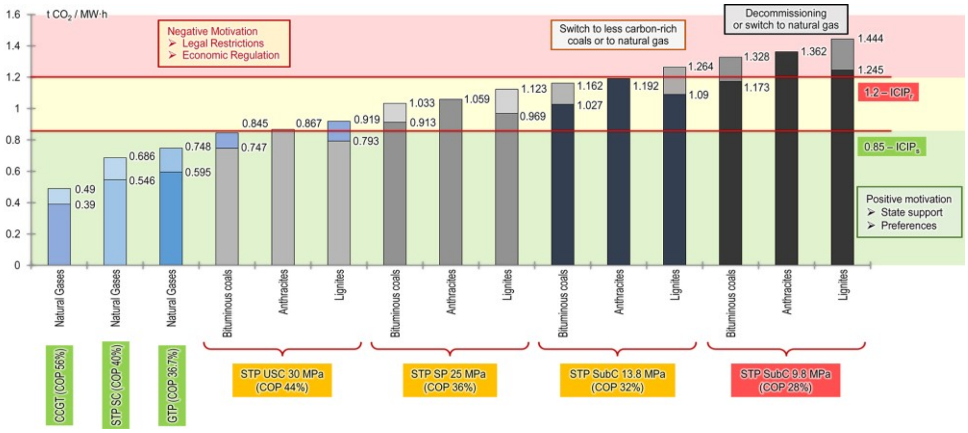

Fig. 2. Carbon intensity: Electricity generation using different Best Available Techniques.

The analysis reveals that gas-fired power plants employing binary condensing CCGT units exhibit the lowest carbon intensity, owing to their high electrical efficiency. CO_2 intensity values for these units range from 0.3 to 0.323 t CO_2/MWh, which is approximately 1.5 times lower than emissions from GTPs and condensing gas-fired STPs and almost 2.5 to 3 times lower than emissions from pulverized coal-fired STPs.

Therefore, priority low-carbon technologies for the Russian electric power industry should include domestically produced GTPs with a capacity over 100 MW and coefficient of performance (COP) exceeding 40% and CCGTs with COP up to 60% [12].

4 Discussion

A sound option for reducing power generation carbon intensity lies in modernization of pulverized coal-fired STPs in such a manner that it will be possible to burn natural gas, provided that this fuel type is available in the region and the modernization is economically feasible. This transition simultaneously addresses energy efficiency improvements and mitigates the environmental impact of thermal power plants by reducing emissions of nitrogen oxides, sulphur dioxide, and fuel ash. This is especially crucial for cities and regions in Siberia and the Far East, where environmental conditions are particularly unfavorable.

However, given Russia's abundant coal reserves and the low cost of coal, the use of this fuel will remain economically dominant in coal-mining regions of Siberia and the Far East for the near future [13]. Therefore, the focus in these regions should be on increasing the efficiency of existing pulverized coal-fired thermal power plants. This can be achieved by gradually retiring outdated and inefficient power plants and replacing older STPs operating at 9.8 MPa/540°C with units that have higher SubC parameters (13.8 MPa/545°C) or SC parameters (25 MPa/545°C).

A particularly important area for these coal-dependent regions is the development and deployment of Russian pulverized coal units with SC parameters (30 MPa/600°C). These units, with their higher efficiency, can reduce CO_2 intensity (t/MWh) by 18–22% [3]. Additionally, the application of the carbon capture, utilization and storage technologies for Russian thermal power plants will be the matter of the nearest future [14, 15].

The most important part lies in establishing two key carbon intensity levels: one for stimulating (encouraging) the leaders ($ICIP_s$) and the other – for "pushing" the outsiders towards reducing GHG emissions to the acceptable levels ($ICIP_r$) (Figure 2). The Figure 2 shows that technologies above the level of $ICIP_r$ are subject to various (presumably – rather stringent) governmental taxes and restrictions while the technological solutions resulting in emissions below $ICIP_s$ are qualified in the Russian legislation as climate friendly projects and may receive government financial support in the form of green loans or bonds. Technologies with carbon intensity between the restrictive and motivational levels fall into the yellow zone as meeting the BAT-related carbon intensity requirements.

The specific $ICIP_r$ and $ICIP_s$ values were determined through analyzing the technologies applied at existing Russian thermal power plants with the overarching goal to promote the BAT implementation in such a manner that will allow to simultaneously improve resource and energy efficiency of energy generation process without excessively high production costs and tariff growth due to various climate-related taxes and quotas.

The stimulating benchmark ($ICIP_s$), set at 0.85 t CO_2/MWh, accommodates technologies falling into the green zone. This zone includes:(Figure 2):

- All power plants (STP, GTP, CCGT) that use gaseous fuels, as they are the most efficient and have lower GHG emissions.
- New pulverized coal-fired SC pressure power plants, which are the most efficient coal-based technologies.

The restrictive benchmark ($ICIP_r$) is set at 1.2 t CO_2/MWh, divides low-efficient carbon intensive energy generating technologies, and indicates the need for modernization in accordance with BAT described in the sectoral Reference Document [4].

It means that coal-fired STPs with SubC parameters (9.8 MPa/540°C) should be gradually replaced with efficient alternatives or converted to natural gas (Figure 2).

More common coal-fired STPs (13.8 MPa/545°C) should undergo a transition to higher-quality coals or natural gas in order to reduce emissions and remain operational (yellow zone).

Advanced STPs with SC parameters (25 MPa/545°C) are free from governmental taxes and quotas and will contribute to national energy prices and tariff stabilization.

Turning to the heat generation, we decided focusing on the carbon intensity of steam and hot water production, which is essential for countries with cold climate exploring urban central heating systems. It is the combination of the combustion techniques and fuel type, which determines the efficiency of boilers. Figure 3 illustrates carbon intensity of heat generation (in tons of CO_2 per Gcal.As it can be seen, burning solid fuels (bituminous coal, anthracite, and lignite) in all cases is characterized by higher specific CO_2 emissions.

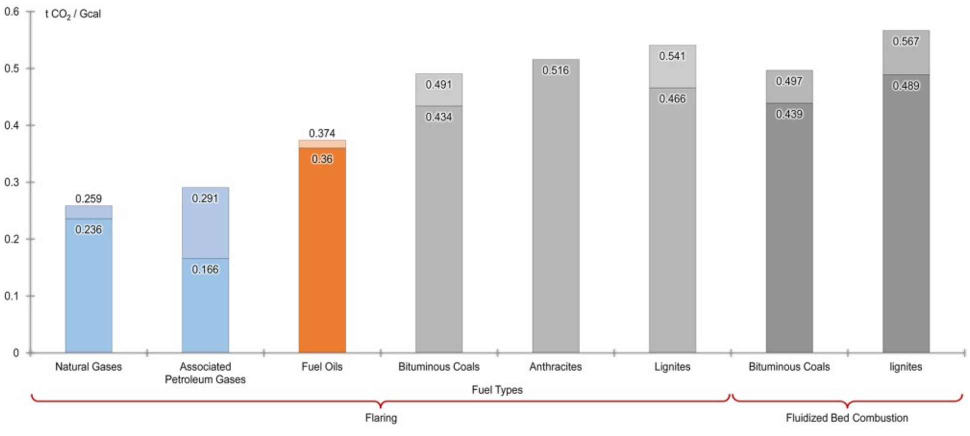

Fig. 3. Carbon intensity: Heat generated from burning various fuels.

For this reason, setting restrictive and stimulating benchmarks for thermal power production emissions is questionable. Instead, decarburization efforts should prioritize transitioning from coal to natural gas combustion and introducing cogeneration systems in large urban areas.

5 Conclusion

The article shows that gas-fired thermal power plant carbon intensity for electricity and heat production (t CO_2/MWh and t CO_2/Gcal) is approximately 50 % lesser than at the coal-fired thermal power stations under comparable conditions. This is a very important issue with regard to turning the national energy sector to more environmentally friendly production more.

Carbon intensity of Russian energy sector depends on not only the fuel type but also the power generating equipment (for example, steam turbine plants with pressures below 13.8 MPa have the highest carbon intensity in comparison to the other boiler types). The most effective approach to the sharp GHG emission reduction lies in BAT-compliant technological modernisation: the coal-fired thermal power plants and standard gas stations should be upgraded combined-cycle gas-fired power plants. This will help to reduce direct CO_2 emissions during electricity production by 1.4–1.5 times compared to standard gas-fired power stations and nearly threefold compared to coal-fired thermal power stations. Another economically feasible option

Boiler modernization of coal-fired power stations to BAT-compliant supercritical parameters will improve efficiency and reduce CO_2 emissions by 18–22%.

The authors performed a benchmarking of energy generating sector and established two key carbon intensity levels (benchmarks): (1) the lower one, for stimulating the leading power plants for the further reduction of GHG emissions, and (2) the upper one, for altering the business “behaviour” of outsiders by imposing various governmental restrictions and fees. The proposed benchmarks should support the decarbonization of Russian thermal power generation while incentivizing the adoption of more efficient technologies without causing a significant rise in wholesale energy prices or consumer tariffs.

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