UDC 338.2
JEL Classification: L61; Q55; Q56; Q58

DECARBONIZATION OF THE STEEL INDUSTRY: THE ROLE OF STATE ECONOMIC POLICY

© 2020 **GLUSHCHENKO A. M.**

UDC 338.2
JEL Classification: L61; Q55; Q56; Q58

Glushchenko A. M.

Decarbonization of the Steel Industry: the Role of State Economic Policy

The aim of the article is to analyze the potential areas of decarbonization of steel production in order to propose government policy measures for reducing CO2 emissions. The study examines the structure of global carbon dioxide emissions, the trends in CO2 emissions from the steel industry, and the environmental policies of the EU and China. Moreover, economic and technological factors complicating the decarbonization of the steel industry are characterized. The main sources of carbon dioxide emissions at steel-producing enterprises are considered. Using the example of a European company, the volume of capital investment for decarbonization of steel production is shown. The key groups of measures that can help solve the problem of CO2 emissions (carbon capture and storage, carbon capture and utilization, prevention of emissions) are identified. The possibilities and limitations for the application of specific decarbonization measures including melting steel in electric arc furnaces, replacing coke with charcoal, using hydrogen in a blast furnace and for direct reduction of iron, and employing electrolysis of iron are analyzed. The carbon intensity of various decarbonization technologies as well as the potential terms for their commercial implementation are compared. As a result of the study, instruments of economic policy for accelerating the decarbonization of the steel industry are identified. The advantages and disadvantages of these instruments are analyzed. The conclusion about the impossibility of decarbonization without state participation, due to the fact that enterprises in the free market do not receive sufficient competitive advantages from investments to considerably reduce CO2 emissions, is made. The prospects for further research are associated with an in-depth study of the instruments of state policy for decarbonization as well as development of directions for decarbonization of other sectors of the economy.

Keywords: *decarbonization, carbon capture and utilization, direct reduction of iron ore, instruments of state financing.*

DOI: *https://doi.org/10.32983/2222-0712-2020-1-340-347*

Fig.: *4.* ***Tabl.:*** *1.* ***Bibl.:*** *19.*

Glushchenko Andrii M. *– Candidate of Sciences (Economics), Analyst, GMK Center, LLC (office 10a, 42-44 Shovkovychna Str., Kyiv, 01004, Ukraine)*

E-mail: *statproff@gmail.com*

ORCID: *http://orcid.org/0000-0002-1897-4837*

УДК 338.2
JEL Classification: L61; Q55; Q56; Q58

Глущенко А. М. Декарбонізація металургії: роль економічної політики держави

Мета статті полягає в аналізі потенційних напрямів декарбонізації металургійного виробництва, щоб запропонувати заходи державної політики, які сприяють зниженню викидів CO_2. У ході дослідження вивчено структуру глобальних викидів вуглекислого газу, динаміку викидів CO_2 металургією, особливості екологічної політики ЄС і Китаю. Також охарактеризовано економічні та технологічні чинники, які ускладнюють декарбонізацію металургії. Розглянуто основні джерела викидів вуглекислого газу на металургійних підприємствах. На прикладі європейської компанії показаний обсяг капітальних інвестицій для декарбонізації виробництва сталі. Виявлено основні групи заходів, що здатні вирішити проблему викидів CO_2 (уловлювання та захоронення CO_2, уловлювання та використання CO_2, запобігання викидам). Проаналізовано можливості й обмеження для використання конкретних заходів декарбонізації, включаючи виплавку сталі в електродугових печах, заміну коксу деревним вугіллям, використання водню в доменній печі та для прямого відновлення заліза, електроліз заліза. Проведено порівняння інтенсивності вуглецевих викидів для різних технологій декарбонізації, а також потенційних термінів їх комерційного впровадження. У результаті дослідження виділено інструменти економічної політики для прискорення декарбонізації металургії. Проаналізовано

УДК 338.2
JEL Classification: L61; Q55; Q56; Q58

Глущенко А. Н. Декарбонизация металлургии: роль экономической политики государства

Цель статьи заключается в анализе потенциальных направлений декарбонизации металлургического производства, чтобы предложить меры государственной политики, способствующие снижению выбросов CO_2. В ходе исследования изучены структура глобальных выбросов углекислого газа, динамика выбросов CO_2 металлургией, особенности экологической политики ЕС и Китая. Также охарактеризованы экономические и технологические факторы, осложняющие декарбонизацию металлургии. Рассмотрены основные источники выбросов углекислого газа на металлургических предприятиях. На примере европейской компании показан объем капитальных инвестиций для декарбонизации производства стали. Выявлены основные группы мер, которые способны решить проблему выбросов CO_2 (улавливание и захоронение CO_2, улавливание и использование CO_2, предотвращение выбросов). Проанализированы возможности и ограничения для использования конкретных мер декарбонизации, включая выплавку стали в электродуговых печах, замену кокса древесным углем, использование водорода в доменной печи и для прямого восстановления железа, электролиз железа. Проведено сравнение углеродоемкости различных технологий декарбонизации, а также потенциальных сроков их коммерческого внедрения. В результате исследования выделе-

переваги та недоліки цих інструментів. Зроблено висновок про неможливість декарбонізації без участі держави, оскільки на вільному ринку підприємства не отримують достатніх конкурентних переваг від інвестицій в значне зниження викидів CO_2. Перспективи подальших досліджень пов'язані з поглибленим вивченням інструментів державної політики декарбонізації, а також розробкою напрямів декарбонізації інших секторів економіки.

Ключові слова: *декарбонізація, уловлювання та використання CO_2, пряме відновлення заліза, інструменти державного фінансування.*

Рис.: *4.* ***Табл.:*** *1.* ***Бібл.:*** *19.*

Глущенко Андрій Миколайович *– кандидат економічних наук, аналітик, ТОВ «ГМК Центр» (вул. Шовковична, 42-44, офіс 10а, Київ, 01004, Україна)*

E-mail: *statproff@gmail.com*

ORCID: *http://orcid.org/0000-0002-1897-4837*

ны инструменты экономической политики для ускорения декарбонизации металлургии. Проанализированы преимущества и недостатки этих инструментов. Сделан вывод о невозможности декарбонизации без участия государства, поскольку на свободном рынке предприятия не получают достаточных конкурентных преимуществ от инвестиций в значительное снижение выбросов CO2. Перспективы дальнейших исследований связаны с углубленным изучением инструментов государственной политики декарбонизации, а также разработкой направлений декарбонизации других секторов экономики.

Ключевые слова: *декарбонизация, улавливание и использование CO_2, прямое восстановление железа, инструменты государственного финансирования.*

Рис.: *4.* ***Табл.:*** *1.* ***Библ.:*** *19.*

Глущенко Андрей Николаевич *– кандидат экономических наук, аналитик, ООО «ГМК Центр» (ул. Шелковичная, 42-44, офис 10а, Киев, 01004, Украина)*

E-mail: *statproff@gmail.com*

ORCID: *http://orcid.org/0000-0002-1897-4837*

Introduction. For a long period of time (from the industrial revolution of the 18th century in England to the beginning of the 1990s), the main attention of government bodies was paid to the economic growth, primarily due to industrial manufacturing, while negative side effects (in the form of environmental problems) remained in the background. With the increasing saturation of markets with industrial products and satisfaction of basic consumer needs, the situation began to change.

In the 1970-1980s, the concept of sustainable development appeared. It was focused on ensuring a balance between economic growth, improvement of social welfare and preservation of the environment. In the 1980s, environmental taxes appeared in the Scandinavian countries. Later, these taxes were adopted by other countries in order to counter environmental pollution.

In 1992, the United Nations Framework Convention on Climate Change was embraced: its participants agreed to take measures to reduce greenhouse gas emissions into the atmosphere. In 1997, the Kyoto Protocol was signed. This document defines specific quantitative obligations of countries to reduce greenhouse gas emissions. In 2015, the Paris Agreement was signed. The purpose of Paris Agreement is to restrain the growth of the average temperature on the planet within 2 °C compared to the pre-industrial era, and ideally reduce the growth to 1.5 °C. Nowadays, the fight against climate change has become the main issue in the environmental agenda. The need for decarbonization of industry is no longer in doubt – the question remains how to achieve it.

Analysis of recent publications. In Ukrainian scientific literature, decarbonization of the economy is not a popular research topic. The Ukrainian economy has important problems that impede its entire development, which is why less attention is paid to environmental issues. Therefore, research on decarbonization is mainly carried out by foreign scientists.

In scientific publications decarbonization is mainly associated with the electric power industry, which is not surprising since the electric power industry is the main source of carbon dioxide emissions. Studies of R. Leal-Arcas, V. Nalule, L. Li, A. Taeihagh, S. I. Melnikova, and others [1-4] analyze the decarbonization experience of the electric power industry in different countries (Malta, Romania, China, the EU). There are also papers considering the decarbonization of other economic sectors: industry in general (R. Duff, M. Lenox [5]) and the steel industry, in particular (L. Hermwille [6]).

The articles published by D. Newbery, J. Meckling, F. Landis, S. Daniele, and others [7-10] are mainly focused on the effectiveness of various instruments of economic policy in the field of decarbonization. Forecasting CO_2 emissions was made by R. B. Jackson with the co-authors [11].

As follows from the review of the literary sources, the scientific discussion still does not pay enough attention to the decarbonization of other economic sectors (outside the electric power industry), in particular, the steel industry. In addition, considering economic policy instruments, studies focus mainly on restrictive measures (taxes, emission limits) while the range of possible instruments is wider.

Therefore, the **purpose** of this article is to analyze the potential decarbonization areas for the steel industry in order to propose government policy measures to reduce the CO_2 emissions.

Research findings. In 2017 the global carbon dioxide emissions amounted to 40 billion tons. The electric power industry was in the first place in terms of the emissions (34 % of the emissions). The buildings sector was in the second place (24 % of the emissions). Transport was in the third place (20 % of the emissions). The steel industry accounted for only 5 % of the global CO_2 emissions (Fig. 1).

From 2015 to 2017 CO_2 emissions in the steel industry fell by 4.8 %, while the global steel production increased by 4.3 % over this period [12, 13]. Thus, increasing the production volumes, the steel industry is gradually improving production processes and striving to reduce CO_2 emissions. First of all, this is stimulated by government bodies, which are responsible for the implementation of environmental policies and international agreements to combat climate change.

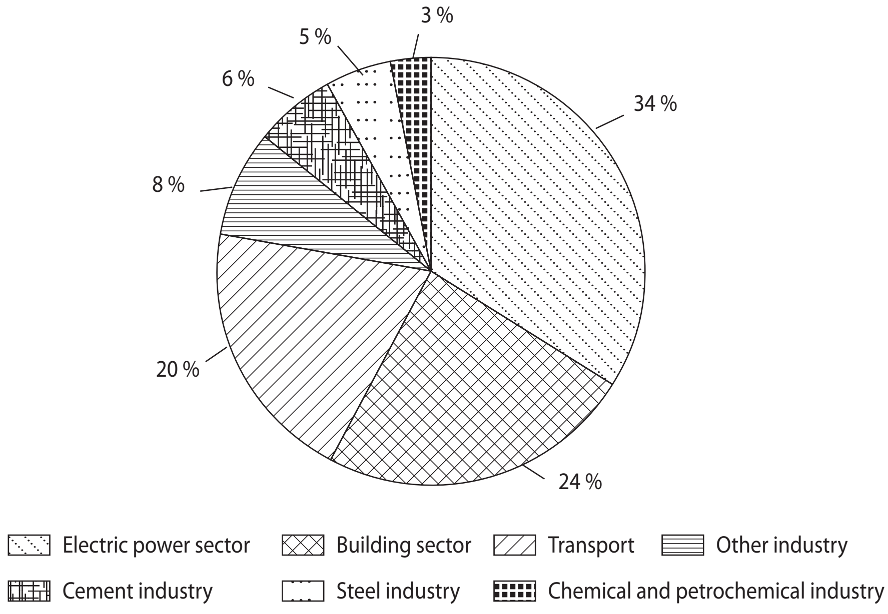

Fig. 1. Sectoral structure of global CO2 emissions in 2017

Source: developed by the author based on [12]

The EU launched the Emissions Trading System (ETS), which sets a limit on greenhouse gas emissions for enterprises. If this limit is exceeded, enterprises are obliged to purchase the missing volumes of quotas in the open market. Free emission limits are decreasing every year, and the price for CO_2 emission allowances is increasing, prompting enterprises to actively reduce emissions.

In 2016–2018, the Chinese government pursued a policy for reducing excessive production capacities in the steel industry. First of all, obsolete production facilities were closed. In total, steel production volume was reduced by150 million tons annually.

In addition, in the autumn-winter period, Chinese authorities impose restrictions on the activities of steel enterprises in order to limit the pollution level.

The volume of restrictions depends on the level of emissions (the lower the level of emissions is, the less production restrictions are). So, it is beneficial for steel plants to carry out environmental modernization since due to it they will be able to continue their activities and not lose profits in the autumn-winter period.

The decarbonization of the steel industry in general goes slow since the following reasons inhibit this process [6; 14]:

a) CO_2 emissions occur at different production stages (sinter plant, coke plant, blast furnace (BF), basic oxygen furnace (BOF) etc.).

At each of the listed stages (Fig. 2), specific efforts are needed to reduce emissions. The source of emissions is also the raw materials used (iron ore, coking coal). At the integrated steel plant, pig iron production is responsible for 70–80 % of CO_2 emissions, of which 24 % are associated with the coke use [5].

Carbon contained in coke releases oxygen from iron ore and reduces iron. Thus, the presence of carbon is a necessary condition for the production process. In addition, carbon is an essential component of steel (up to 1 % in high-carbon grades).

b) steel production requires heating to a high temperature. According to McKinsey's estimates, 45 % of CO2 emissions at a steel plant are associated with high-temperature heating (over 500 °C) [14]. Few alternative technologies may be suitable for this purpose. In addition, these technologies are at the initial development level (biomethane, hydrogen).

c) the various stages of steel production are deeply integrated with each other. A change at one stage entails the need for changes at other stages. Therefore, to reduce CO2 emissions, the entire production chain needs to be changed.

d) the introduction of new technologies at existing steel plants requires high capital investments. According to Voestalpine, under the current conditions, the decarbonization of steel production (annual capacity – 7.5 million tons of steel) will require:

- 7 billion euros for the introduction of a breakthrough technology (direct reduction of iron with hydrogen);
- 3 billion euros for the electrolysis unit, which will produce hydrogen from water;
- 20 billion euros for the renewable electricity generation by wind farms. This electricity will be used in the hydrogen electrolysis [16].

e) the use of low-carbon technologies leads to an increase in production costs. Countries that impose low CO2 requirements actually reduce the competitiveness of domestic producers.

There are several parallel decarbonization directions in the steel industry (Fig. 3).

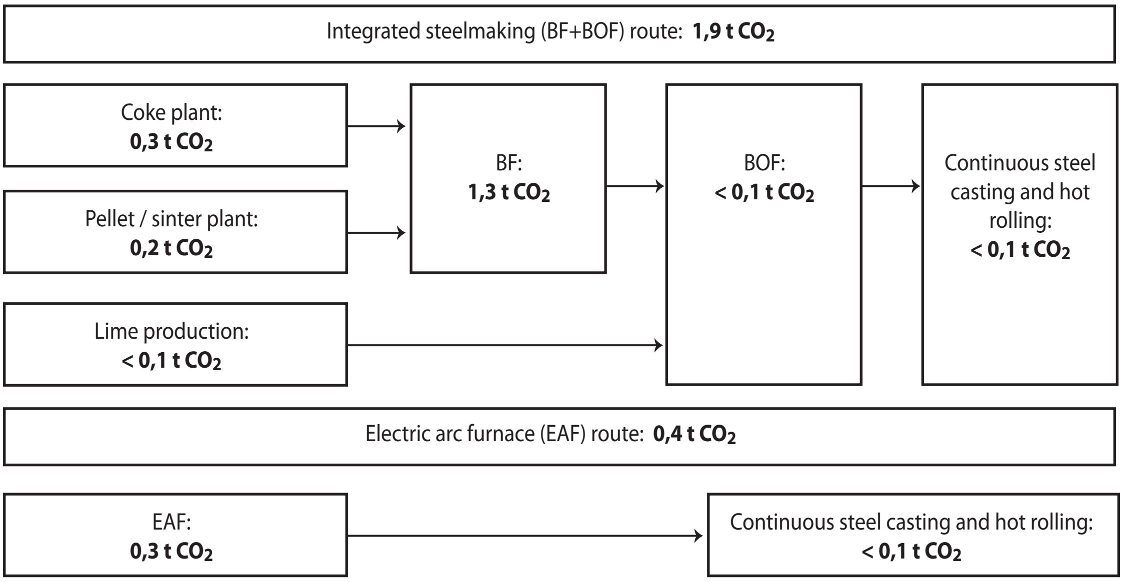

Fig. 2. CO_2 emissions at the stages of steel production, tons of CO_2 per ton of steel

Source: [15]

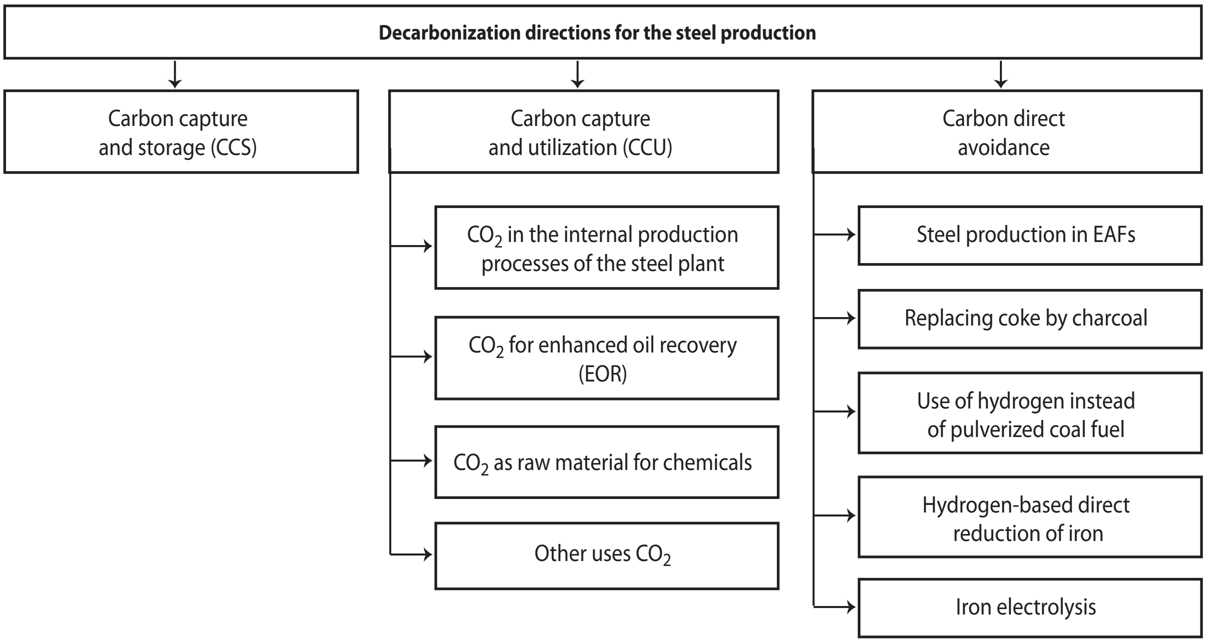

Fig. 3. Decarbonization directions for the steel production

Source: developed by the author based on [6; 14; 15; 17]

Carbon capture and storage (CCS) involves separation of carbon dioxide from emission sources and subsequent permanent isolation from the atmosphere (usually in the underground storage).

Carbon capture and utilization (CCU) is a similar process, which differs in one feature – CO_2 is not just stored in special storage facilities but is used in other production processes. This is the advantage of such technologies – CO_2 generates revenue, increasing the economic feasibility of its capture. The most interesting opportunities for carbon utilization include:

a) the CO_2 conversion into synthesis gas, which is fed into the blast furnace instead of coke and pulverized coal fuel (IGAR project implemented by ArcelorMittal);
b) CO_2 injection into oil wells to increase their debit (enhanced oil recovery);
c) production of methanol, polymers, ammonia, higher alcohols (Carbon2Chem project implemented by Thysenkrupp);
d) bioethanol production (Steelanol project implemented by ArcelorMittal);

e) naphtha production (Everest project implemented by Tata Steel).

Currently, the application of CCU/CCS technologies in the steel industry is complicated because of several emission sources, which makes it difficult to capture more than 60 % of CO_2 [15].

A possible solution to the problem is the transition to smelting reduction. It allows pig iron to be smelted in one production unit, into which coal (not necessarily coking) and iron ore are loaded.

Accordingly, the sinter plant, the coke plant, the blast furnace are excluded from the production process, and CO_2 emissions are concentrated in one place.

An alternative is to increase the use of blast furnace gases in steel production and to capture the remaining CO_2 emissions.

Steel production in EAFs is the most advanced technology to prevent CO_2 emissions. Scrap is used as the main raw material. The spread of this technology is restrained by such factors as the scrap availability, the degree of scrap contamination with various impurities, especially copper (worsen the quality of produced steel), the need to supply large electricity volumes for the electric arc furnaces. In addition, the transition to renewable energy sources is also necessary for a successful decarbonization of EAFs. This step will eliminate CO_2 emissions associated with electricity generation.

Replacing coke by charcoal can be used only in mini-blast furnaces. The use of charcoal instead of coke can reduce CO_2 emissions by 32–58 % [18]. This approach is practiced by Brazilian enterprises that grow eucalyptus on special plantations and then produce charcoal from it. New seedlings are immediately planted in place of felled trees. Eucalyptus resources are renewed every 6–7 years.

For many countries (including Ukraine), replacing coke with charcoal is not suitable for the following reasons: firstly, the lack of appropriate forest resources; secondly, the large size of existing blast furnaces; thirdly, the transition to small blast furnaces will lead to increased energy costs and losses of competitiveness by domestic producers.

The use of hydrogen instead of pulverized coal fuel for a blast furnace is possible since hydrogen, like carbon, is able to reduce iron from iron ore. The advantage of hydrogen is that when it is used, water vapor is released instead of CO_2. Currently the use of hydrogen in a blast furnace is being investigated at the ThyssenKrupp plant in Germany.

Direct reduction of iron ore is a manufacturing process that provides alternative raw materials for electric arc furnaces: DRI-pellets (DRI – Direct Reduced Iron) and hot briquetted iron (HBI). For these products rich iron ore (with iron content of at least 70 %) is used. Such ore is reduced at high temperatures to iron content of 90 % or more. Natural gas is used as a traditional reducing agent.

Direct reduction of iron ore followed by steel production in EAF emits 40 % less CO2 compared to the BF-BOF route (Fig. 4). However, in the EU, as in Ukraine, direct reduction of iron ore is not common due to the lack of cheap natural gas. The production of DRI and HBI is concentrated mainly in the Middle East, North Africa and Latin America. The main idea for reducing emissions is to replace natural gas with hydrogen. The possibility of using hydrogen to reduce iron ore does not raise questions – in a conventional DRI production process, which is based on natural gas, hydrogen reduces up to 50 % of iron ore, the rest is reduced by carbon.

However, the transition to hydrogen for the decarbonization purpose raises a number of challenges. Firstly, hydrogen should be produced without CO_2 emissions. This can be achieved either by capturing carbon dioxide (in the production of hydrogen from natural gas) or using alternative sources of electricity (in the production of hydrogen by water electrolysis).

Secondly, there is a need to create hydrogen storage facilities.

Thirdly, to reduce CO_2 emissions throughout the whole production chain, alternative energy sources are needed for sintering / pelletizing iron ore as well as for the EAFs and furnaces that heat billets before rolling.

The iron electrolysis begins from iron ore dissolution in an electrolyte (molten oxide or a mixture of oxides, e. g, calcium oxide, aluminum oxide, magnesium oxide) at about 1600 °C.

Then an electric current is passed through this solution. As a result, reduced iron is collected on the cathode, and oxygen is on the anode. This method is at the stage of laboratory research. Siderwin is the most famous iron electrolysis project, which is implemented by ArcelorMittal.

Among the methods that prevent CO2 emissions, the most promising are electric arc steelmaking and hydrogen-based direct reduction of iron ore. These breakthrough technologies can reduce CO2 emissions to almost zero (Fig. 4).

At the same time, considering potential implementation speed, the most likely candidates to be applied in the steel industry are CCS/CCU technologies (Tbl. 1).

An active state policy can accelerate the decarbonization of the steel industry. Such policy should include the following measures:

- *Development and implementation of long-term plans for decarbonization.*

Such plan should coordinate the actions of various economic sectors, in particular, steel industry and electric power industry (the development of alternative electric power industry is a necessary condition for decarbonization of steel production). The plan should also include steps to develop an appropriate infrastructure for the transportation and storage of hydrogen, CO_2, etc.

On the one hand, an indicative decarbonization plan will help companies improve their business planning. On the other hand, this plan should involve specific actions of the state institutions.

- *Reduction of import tariffs on equipment needed for decarbonization.*

This measure reduces capital expenses and encourages enterprises to invest in the decarbonization projects. The state refuses part of the potential tax revenues in exchange for the implementation of environmental projects.

- *Limiting exports of raw materials used in low-carbon technologies.*

It allows fully meeting the needs of domestic manufacturers in materials necessary for decarbonization as well as preventing a surge in prices.

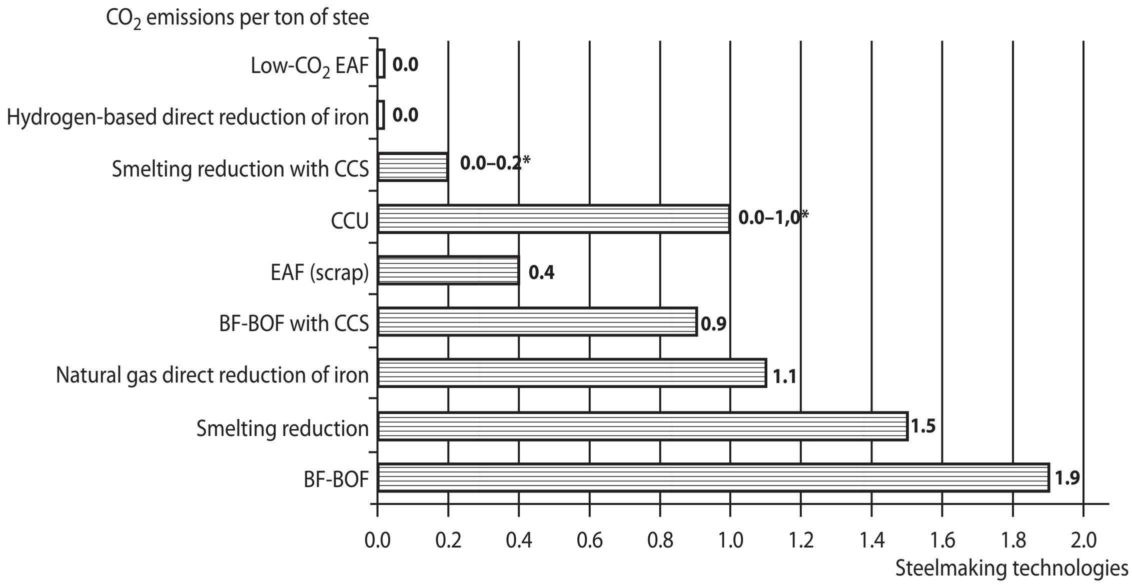

Fig. 4. Carbon intensity of different steelmaking technologies, CO2 emissions per ton of steel

* – depends on the technologies used

Source: [15]

Table 1

Prospects for the commercialization of decarbonization technologies

Technology	Potential implementation period
Blast furnace with carbon capture	5-10 years
Carbon capture and utilization in BF-BOF route	5-10 years
Conventional DRI production (existing DRI technology + CCU)	5-10 years
DRI production based on green hydrogen (produced from water with help of clean electricity)	10-20 years
DRI production based on hydrogen received from natural gas (with CCS)	10-20 years
Iron electrolysis	20-30 years

Source: developed by the author based on [19]

- *Increase in carbon dioxide emission charges (implemented in the mechanism of the EU Emissions Trading System).*

Logically, the increase in costs associated with CO2 emissions strengthens the interest of enterprises in carrying out environmental modernization. Accordingly, enterprises must reduce their CO2 emissions to avoid ever-increasing emissions costs.

However, in practice there arise problems:

1) increase in emission charges may not be in line with the technological capabilities of decarbonization;
2) the problem of finding sources for financing environmental activities is not being resolved;
3) an increase in the charge for CO_2 emissions should be implemented synchronously in all countries. Otherwise, manufacturers from countries where CO_2 charges are low or absent will receive competitive advantages. Accordingly, there will be stimuli to transfer polluting industries to countries with low environmental standards and global emissions will not be reduced.

- *Import restrictions for products manufactured with high CO_2 emissions.*

It can be implemented in the EU in the form of carbon border adjustment (carbon border tax) – a special tax tied to the difference in CO_2 emissions from steel production in different countries and the difference in costs related to payments for CO_2 emissions.

It is a response to gaining competitive advantages by producers from countries where CO2 charges are low or absent.

- *Development of product standards that allow only low CO_2 emissions.*

It can be used in combination with other measures. Its isolated use will lead to an increase in the production costs and the crowding out of environmentally friendly products since manufacturers from countries with low environmental standards will gain competitive advantages.

- *Simplification of patent procedures for decarbonization technologies.*

It is a regulatory measure aimed at reducing the patenting costs for relevant technologies and accelerating their launch.

- *State funding for decarbonization projects.*

Currently, many decarbonization technologies are at an initial level of development. The state is involved in financing their development, especially for scaling them from laboratory research to commercial use opportunities.

Government financing tools are grants, loans, loan guarantees, interest rate compensation.

Furthermore, enterprises can be provided with tax incentives in case of implementation of decarbonization projects.

- *Measures in the employment field*.

They are necessary for providing new production processes with qualified staff and finding jobs for employees dismissed during the "green transition".

Conclusions. Decarbonization of the steel industry is a complex process that will change this sector in general. To successfully reduce CO_2 emissions, several conditions must be met including the availability of appropriate decarbonization technologies (ready for commercial use), the ability of enterprises to implement these technologies (including the ability to attract external financing for decarbonization projects), and protecting the domestic market from import inflows of products that are produced with large CO_2 emissions. Each of these conditions implies a specific economic policy of the state. Without state participation, decarbonization is impossible since for enterprises investments in reducing CO_2 emissions are additional costs that do not allow increasing competitiveness compared to other enterprises that do not bear such costs.

The task of state authorities is to make decarbonization mandatory for everyone (both for domestic producers and importers). Only in this case decarbonization will lead to a real reduction of harm to the environment. To achieve this result, it is necessary to continue research on separate instruments of the state decarbonization policy and directions for decarbonization of other economic sectors.

LITERATURE

1. Leal-Arcas R., Filis A., Nalule V. Energy decentralization and decarbonization: The case of Romania and Malta. *Natural Resources Journal*. 2020. Vol. 60. No 1. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3460016

2. Leal-Arcas R., Peykova M., Nalule V., Kara P. Decarbonizing the Energy Sector. *Journal of Animal & Natural Resource Law.* 2019. Vol. 15. P. 173–272.

3. Li L., Taeihagh A. An in-depth analysis of the evolution of the policy mix for the sustainable energy transition in China from 1981 to 2020. *Applied Energy.* 2020. Vol. 263. P. 1–12.

DOI: 10.1016/j.apenergy.2020.114611

4. Мельникова С. И. Декарбонизация европейской энергетики: цели и реалии. *Современная наука: исследования, идеи, результаты, технологии.* 2013. Вып. 2. С. 168–172.

5. Duff R., Lenox M. Path to 2060: Decarbonizing the Industrial Sector. *Batten Report.* 2018. P. 1–30. URL: https://www.researchgate.net/publication/329810198_Path_to_2060_Decarbonizing_the_Industrial_Sector

6. Hermwille L. Exploring the Prospects for a Sectoral Decarbonization Club in the Steel Industry. *COP21 RIPPLES – COP21: Results and Implications for Pathways and Policies for Low Emissions European Societies.* 2019. P. 1–35. URL: https://www.cop21ripples.eu/wp-content/uploads/2019/09/20190829_COP21-RIPPLES_D4-3d_Steel-Sector-Decarbonization-Club.pdf

7. Newbery D. Policies for decarbonizing a liberalized power sector. *Economics E-Journal*. 2018. P. 1–28.

DOI: 10.5018/economics-ejournal.ja.2018-40

8. Meckling J., Sterner T., Wagner G. Policy sequencing toward decarbonization. *Nature Energy.* 2017. No 2. P. 918–922.

DOI: 10.1038/s41560-017-0025-8

9. Multi-model comparison of Swiss decarbonization scenarios / Landis F. [et al]. *Swiss Journal of Economics and Statistics*. 2019. Vol. 155. No 12. P. 1–18. DOI: 10.1186/s41937-019-0040-8

10. Daniele S., Filomena G., Nicoletta L., Aristide G. Cost-benefit analysis to support decarbonization scenario for 2030: A case study in Italy. *Energy Policy*. 2020. Vol. 137.

DOI: 10.1016/j.enpol.2019.111137

11. Global energy growth is outpacing decarbonization / Jackson R. B. [et al.]. *Envrionmental Research Letters.* 2018. Vol. 13. No 12.

DOI: 10.1088/1748-9326/aaf303

12. Tracking Industry // IEA. Paris, 2019. URL: https://www.iea.org/reports/tracking-industry

13. Steel Statistical Yearbook 2018 // World Steel association. 121 p. URL: https://www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf

14. Decarbonization of industrial sectors: the next frontier / A. de Pee [et al.]. Amsterdam : Mc Kinsey, 2018. 63 p.

15. Industrial Transformation 2050. Pathways to net-zero emissions from EU heavy industry // Material economics. 2019. 207 p. URL: https://materialeconomics.com/publications/industrial-transformation-2050

16. The European Steel. The wind of change / Edited by N. Lucas and D. R. de Valdalbero. Luxembourg, 2018. 35 p.

DOI: 10.2777/236603

17. Low carbon roadmap. Pathways to a CO_2-neutral European steel industry / Eurofer. Brussels, 2019. p. 18.

18. Tracking industrial energy efficiency and CO_2 emissions // IEA. Paris, 2007. 321 p. URL: https://webstore.iea.org/tracking-industrial-energy-efficiency-and-co2-emissions

19. ArcelorMittal Climate Action Report 1. May 2019. URL: https://corporate.arcelormittal.com/~/media/Files/A/ArcelorMittal/investors/corporate/AM_ClimateActionReport_1.pdf

REFERENCES

"ArcelorMittal Climate Action Report 1". May 2019. https://corporate.arcelormittal.com/~/media/Files/A/ArcelorMittal/investors/corporate/AM_ClimateActionReport_1.pdf

Daniele, S. et al. "Cost-benefit analysis to support decarbonization scenario for 2030: A case study in Italy". *Energy Policy*, vol. 137 (2020).

DOI: 10.1016/j.enpol.2019.111137

De Pee, A. et al. *Decarbonization of industrial sectors: the next frontier*. Amsterdam: Mc Kinsey, 2018.

Duff, R., and Lenox, M. "Path to 2060: Decarbonizing the Industrial Sector". Batten Report. 2018. https://www.researchgate.net/publication/329810198_Path_to_2060_Decarbonizing_the_Industrial_Sector

Hermwille, L. "Exploring the Prospects for a Sectoral Decarbonization Club in the Steel Industry". COP21 RIPPLES - COP21: Results and Implications for Pathways and Policies for Low Emissions European Societies. 2019. https://www.cop21ripples.eu/wp-content/uploads/2019/09/20190829_COP21-RIPPLES_D4-3d_Steel-Sector-Decarbonization-Club.pdf

"Industrial Transformation 2050. Pathways to net-zero emissions from EU heavy industry". Material economics. 2019. https://materialeconomics.com/publications/industrial-transformation-2050

Jackson, R. B. et al. "Global energy growth is outpacing decarbonization". *Envrionmental Research Letters*, vol. 13, no. 12 (2018).

DOI: 10.1088/1748-9326/aaf303

Landis, F. et al. "Multi-model comparison of Swiss decarbonization scenarios". *Swiss Journal of Economics and Statistics*, vol. 155, no. 12 (2019): 1-18.

DOI: 10.1186/s41937-019-0040-8

Leal-Arcas, R. et al. "Decarbonizing the Energy Sector". *Journal of Animal & Natural Resource Law*, vol. 15 (2019): 173-272.

Leal-Arcas, R., Filis, A., and Nalule, V. "Energy decentralization and decarbonization: The case of Romania and Malta". Natural Resources Journal. 2020. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3460016

Li, L., and Taeihagh, A. "An in-depth analysis of the evolution of the policy mix for the sustainable energy transition in China from 1981 to 2020". *Applied Energy*, vol. 263 (2020): 1-12.

DOI: 10.1016/j.apenergy.2020.114611

Low carbon roadmap. Pathways to a CO2-neutral European steel industry. Brussels: Eurofer, 2019.

Meckling, J., Sterner, T., and Wagner, G. "Policy sequencing toward decarbonization". *Nature Energy*, no. 2 (2017): 918-922.

DOI: 10.1038/s41560-017-0025-8

Melnikova, S. I. "Dekarbonizatsiya yevropeyskoy energetiki: tseli i realii" [Decarbonization of European Energy: Goals and Realities]. *Sovremennaya nauka: issledovaniya, idei, rezultaty, tekhnologii*, no. 2 (2013): 168-172.

Newbery, D. "Policies for decarbonizing a liberalized power sector". *Economics E-Journal* (2018): 1-28.

DOI: 10.5018/economics-ejournal.ja.2018-40

"Steel Statistical Yearbook 2018". World Steel association. https://www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf

"Tracking industrial energy efficiency and CO2 emissions". IEA. Paris, 2007. https://webstore.iea.org/tracking-industrial-energy-efficiency-and-co2-emissions

"Tracking Industry". IEA. Paris, 2019. https://www.iea.org/reports/tracking-industry

The European Steel. The wind of change. Luxembourg, 2018.

DOI: 10.2777/236603

Стаття надійшла до редакції 13.02.2020 р.