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DECARBONISATION PATHWAYS OF THE STEEL INDUSTRY

ŚCIEŻKI DEKARBONIZACJI PRZEMYSŁU STALOWEGO

The article was prepared on the basis of reports from the Green Steel for Europe (GREENSTEEL) project funded by the European Union as part of the implementation of the climate and energy goals for 2030 and the long-term strategy for a climate neutral Europe by 2050. A consortium of implementers composed of ten partners from EU countries, including Łukasiewicz – Institute for Ferrous Metallurgy in Gliwice, has identified promising technologies for the decarbonisation of the steel industry, defined technological pathways constituting process chains composed of these technologies, as well as scenarios of the decarbonisation process until 2030 and until 2050.

The end result of the project is a set of insights and recommendations for effective clean steel manufacturing solutions suitable for the EU to achieve the EU's climate and energy goals.

Keywords: *iron and steel industry, decarbonisation, hydrogen use, biomass coal, metallurgy based on electricity, technological pathways*

Artykuł opracowano na podstawie raportów z realizacji projektu pt. „Zielona stal dla Europy – Green Steel for Europe" (GREENSTEEL) sfinansowanego ze środków Unii Europejskiej w ramach realizacji celów klimatycznych i energetycznych na 2030 r. oraz długoterminowej strategii na rzecz Europy neutralnej dla klimatu do 2050 r. Konsorcjum realizatorów złożone z dziesięciu partnerów z krajów UE, w tym Łukasiewicz – Instytut Metalurgii Żelaza w Gliwicach, zidentyfikowało obiecujące technologie dekarbonizacji przemysłu stalowego, określiło ścieżki technologiczne stanowiące łańcuchy procesów złożone z tych technologii, a także scenariusze procesu dekarbonizacji do 2030 i do 2050 roku.

Efektem końcowym projektu jest zbiór spostrzeżeń i zaleceń dotyczących skutecznych rozwiązań w zakresie czystej produkcji stali, odpowiednich dla UE, aby osiągnąć cele klimatyczne i energetyczne UE.

Słowa kluczowe: *hutnictwo żelaza i stali, dekarbonizacja, wykorzystanie wodoru, węgiel z biomasy, metalurgia oparta na energii elektrycznej, ścieżki technologiczne*

1. INTRODUCTION

The objectives of the European Commission (EC) in the field of climate and energy by the end of 2030 assume, among others, the reduction of greenhouse gas emissions in the European Union (EU) in all sectors of the economy by at least 40 % from the 1990 level, as well as at least 32 % share of renewable energy in total energy consumption and improvement of energy efficiency by at least 32.5 %. The goal of the long-term strategy of the EC is to achieve climate neutrality by 2050.

The iron and steel industry is currently responsible for 7 % of total CO_2 emissions. They include direct CO_2 emissions resulting mainly from the use of coal and coke as reducing agents and energy carriers, and indirect emissions related to the production of electricity for the needs of the iron and steel industry in power plants fired with hard coal, lignite, coke and hydrocarbon gases. As a result, the European steel industry requires a fundamental change in the technology of iron and steel production, as well as in the sources of the necessary energy, which will result in a significant increase in costs.

Steel is an alloy of iron with other elements, including carbon, and in the process of its production, a number of oxidation and reduction reactions take place, so CO_2 emissions cannot be completely eliminated. In order to achieve the European climate and energy targets for 2050, CO_2 emissions in the iron and steel industry must be reduced by 80–95 % compared to 1990 levels by then.

The implementation of the assumptions of the EU climate and energy policy requires it to support the advancement of existing solutions and develop new solutions in the field of steel production without greenhouse gas emissions.

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One of such undertakings was the "Green Steel for Europe" project, acronym GREENSTEEL, implemented in recent years. A consortium of implementers composed of ten partners, representing: an analytical centre, research units (including Łukasiewicz – Institute for Ferrous Metallurgy) and industrial units, a European industrial association and the European Steel Technology Platform, identified promising decarbonisation technologies, defined technological pathways constituting chains of processes composed of these technologies, as well as scenarios of the decarbonisation process until 2030 and 2050. When developing the scenarios, a number of important factors – barriers – were taken into account: technological, economic, social and legal, including: availability of resources and infrastructure, maturity of technology, specific conditions in given countries, production costs, etc.

This article was developed on the basis of reports on the implementation of the GREENSTEEL project and literature data, with particular emphasis on conference and seminar materials from the implementation of the Research Fund for Coal and Steel (RFCS) project, supporting research and innovation in the field of low-emission steel production under the name Green Steel for Europe (GREENSTEEL), including the following seminars: "Low-Carbon Future" of 24 March 2020, "Green steel by EAF route: sustainable value chain in the EU Circular Economy Scenario of 13–14 November 2019, reports on the implementation of the GREENSTEEL project and own materials.

2. IRON AND STEEL PRODUCTION TECHNOLOGIES REDUCING CO_2 EMISSIONS IN THE STEEL INDUSTRY

According to the adopted premises, it is assumed that the decarbonisation of the steel industry in the EU will proceed gradually and should be completed by 2050. During this period, it is planned to refine and implement both transitional and target technologies and combine them into appropriately optimised systems.

Reducing CO_2 emissions in metallurgical processes requires the elimination of coal as a fuel and reducer, and wherever the formation of CO_2 cannot be avoided, the capture and use (CCU – carbon capture and usage) or sequester (CCS – carbon capture and storage) the gas. When the use of coal is necessary, it should be done in a sensible way to minimise CO_2 emissions, and use carbon from biomass or recycled plastics, used tires, etc., the emissions of which are not accounted for. In view of the above, the methods of implementing a low-carbon economy in the steelmaking process include carbon direct avoiding techniques (CDA – carbon direct avoiding) and techniques implementing smart usage (SCU – smart carbon usage) (Fig. 1) [1]. Smart use of coal involves the integration of current iron and steel production techniques with new, emission-reducing methods (PI – processes integration).

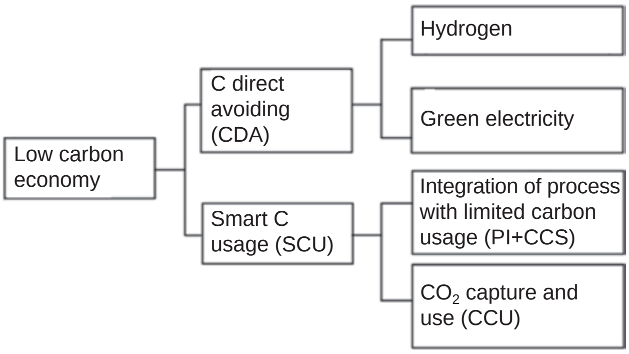

Fig. 1. Ways of low-carbon economy implementation in the steel industry [1]

Rys. 1. Sposoby realizacji gospodarki niskowęglowej w procesie wytwarzania stali [1]

Direct carbon avoidance (CDA) in the production of steel from iron ore can be implemented using hydrogen metallurgy processes and processes using electricity obtained from renewable or emission-free sources (e.g. nuclear power) (Fig. 2).

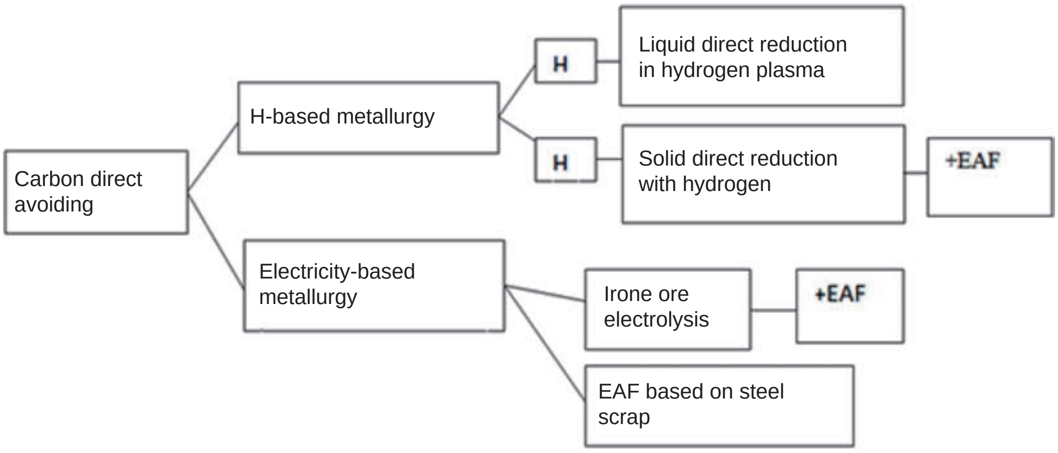

Fig. 2. Realisation of the idea of direct avoidance of coal in steelmaking processes [1]

Rys. 2. Realizacja idei bezpośredniego unikania węgla w procesach stalowniczych [1]

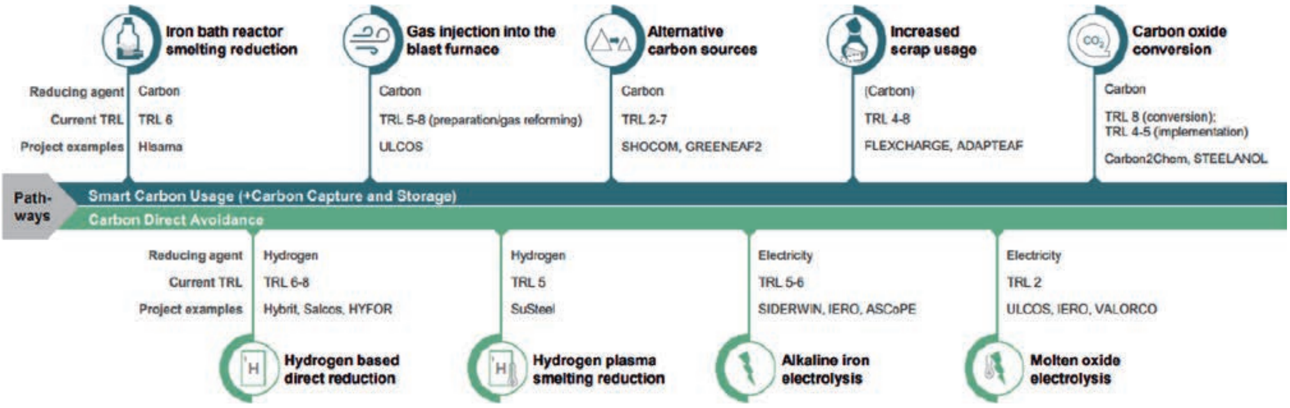

Fig. 3. Promising techniques of producing steel with low CO_2 emissions [2]

Rys. 3. Obiecujące techniki wytwarzania stali z niską emisją CO_2 [2]

The result will be the elimination of coking plants, blast furnaces and converters, and the replacement of fossil fuels with green hydrogen and/or electricity.

Hydrogen-based metallurgical processes are direct reduction in the liquid state, in hydrogen plasma and in the solid state using hydrogen.

In the group of metallurgical processes based on electricity, the following should be distinguished: electrolysis of iron ore followed by smelting in electric arc furnaces and scrap steelmaking process in electric arc furnace.

The smart use of carbon (SCU) will consist in:
- modification and integration pf processes in existing steelworks (PI – process integration),
- smart use of fossil fuels (carbon, natural gas, etc.) to reduce CO_2 emissions.

The following were recognised as auxiliary technologies for the above: capture and use of CO_2 and production of hydrogen.

As a result of the implementation of the “GREENSTEEL” project, based on the analysis of publications, consultations with interested parties (steel-producing companies, research and analytical facilities) and conclusions from the LowCarbonFuture project, previously carried out also under the Research Fund for Coal and Steel (RFCS), nine promising technologies for iron and steel production were distinguished, which are assumed to enable the decarbonisation of the steel industry [2]. They form two groups (Fig. 3), of which:

- the first includes technologies characterised by the smart use of coal:
  - direct reduction in liquid state in a liquid iron reactor (iron bath reactor smelting reduction),
  - injection of hydrocarbon gas – natural gas, biogas, etc. – into a blast furnace,
  - alternative sources of coal: biomass, plastics,
  - increased use of scrap,
  - use of generated CO_2 for the production of fuels, plastics, semi-finished products for the chemical industry,
- the other includes carbon-free technologies:
  - direct reduction in the solid state using hydrogen,
  - indirect reduction in the liquid state with hydrogen plasma,
  - electrolysis of alkali iron ore,
  - electrolysis of liquid iron ore.

2.1. TECHNOLOGIES INVOLVING SMART USE OF COAL

The Hisarna process is an example of a technology with the smart use of coal based on the reduction of iron oxides in the liquid state (IBRSR – iron bath reactor smelting reduction) with a carbon reducer in a reactor for the production of liquid iron. It involves a two-stage processing of non-agglomerated iron ore into liquid pig iron using pulverised coal. In the first stage, the ore is melted in a high-temperature unit (cyclone converter furnace – CCF), and in the second, the final stage of reduction with coal dust (smelting reduction vessel – SRV) to liquid iron takes place (Fig. 4). This technology allows to reduce the

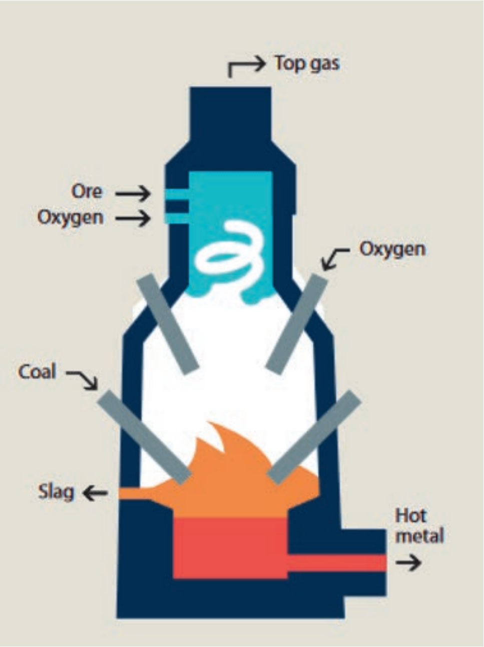

Fig. 4. HISARNA process in a reactor [4]

Rys. 4. Reaktor realizujący proces HISARNA [4]

carbon footprint by 50 % compared to the traditional process of producing pig iron in a blast furnace, without the need for carbon dioxide capture technology [3, 4].

There are also plans to improve this technology to increase the environmental benefits through:
- substituting injected fossil coal with coal from biomass,
- substituting a part of iron ore with scrap,
- application of CO_2 capture and utilisation technology due to the fact that process gases are mainly pure CO_2.

Technologies consisting in injecting hydrocarbon gases into a blast furnace allow partial replacement of coal and coke, reducing CO_2 emissions. For this purpose, natural gas, biogas, coke oven gas and blast furnace gas, as well as pure hydrogen obtained using renewable – green – energy sources can be used. In addition, it is also possible to replace natural gas in burners with biogas or metallurgical process gases with their enrichment with the addition of green H_2. The technology combining the injection of recirculated blast furnace gas, after it is purified and heated, with the injection of pulverised coal and oxygen, developed under the ULCOS project, currently at the 7th TRL development level, is an example of practical application of these processes. A pilot installation with a capacity of 1.5 Mg pig iron/h operates in Sweden and an industrial demonstration plant is under construction.

Another example is the technology being developed in Japan (Fig. 5) as part of the COURSE50 project – (CO_2 Ultimate Reduction System for Cool Earth 50), which consists in replacing part of the coke in the blast furnace with a hydrogen reducer from injected coke oven gas. In addition, CO_2-treated blast furnace gas is recycled to the blast furnace. In the case of the hydrogen reduction ironmaking process, extremely high coke strength is required to maintain adequate gas flow in the blast furnace. A significant improvement in coke strength is to be provided by a special caking additive (HPC – High Performance Caking additive) to the mixture [5, 6].

Technologies using alternative coal sources consist in the use of renewable raw materials and energy in order to at least partially replace fossil coals and their derivatives (coke) in iron and steel production processes. Alternative sources of carbon include: raw biomass or its biochars and/or secondary carbon-bearing materials (plastics, car tyres). The use of charcoal in blast furnaces as a fuel, either by adding to the batch mix or by blowing through nozzles, as well as gasification of coal-bearing waste and injection of the produced gas, or the use of waste plastics is an example of practical implementation in the blast furnace process. Technologies in this field were developed, among others, within the SHOCOM project [7].

In the electric arc process, chars from biomass introduced with the charge in the loading hopper can

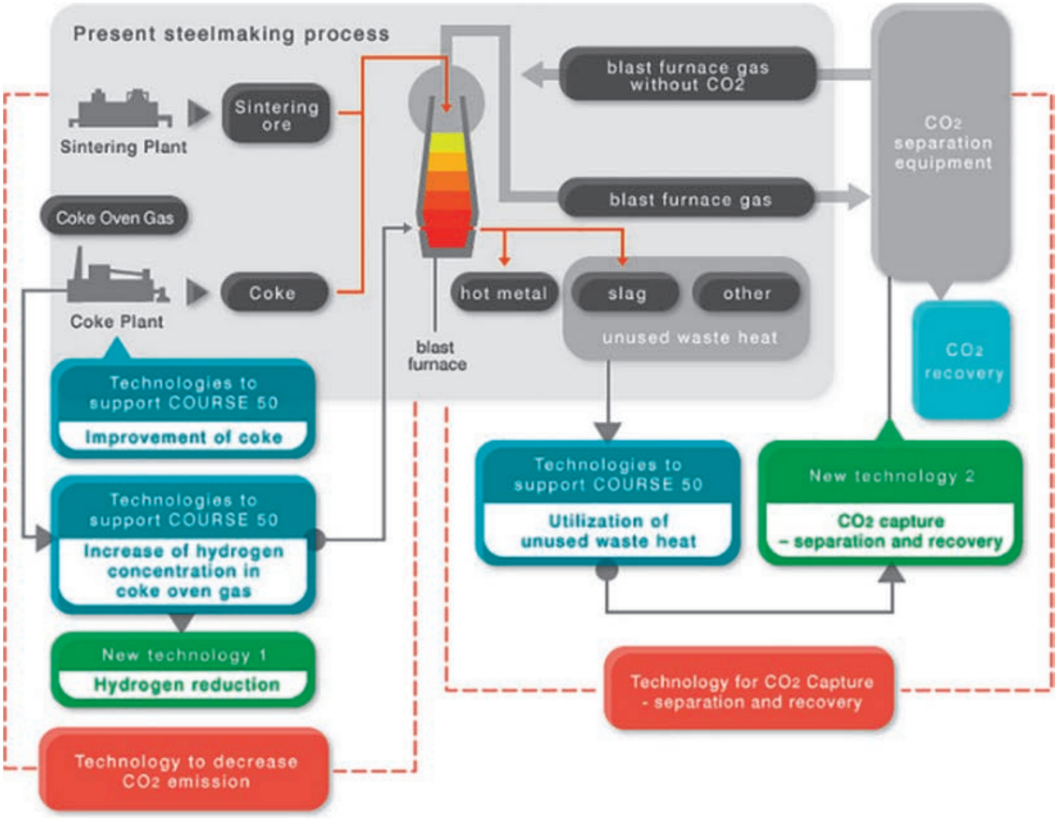

Fig. 5a. Project COURSE50 [5]

Rys. 5a. Projekt COURSE50 [5]

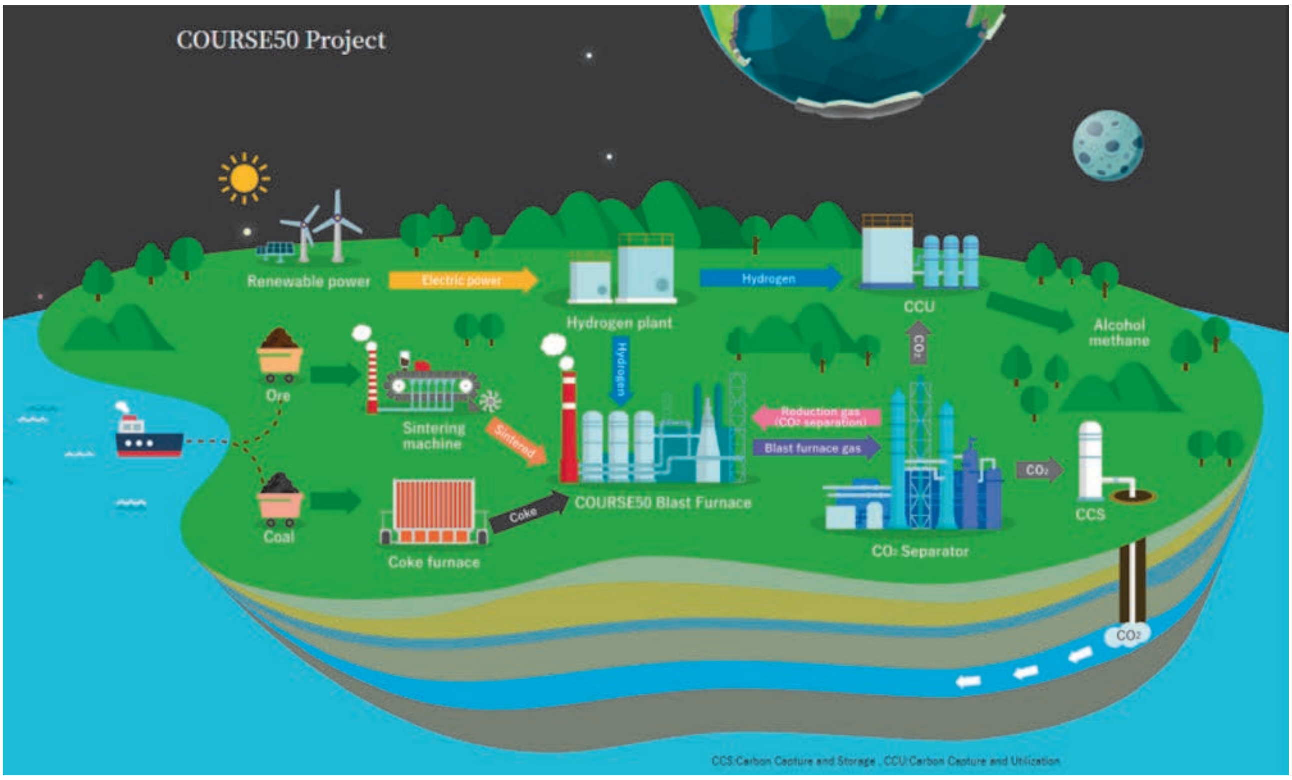

Fig. 5b. Idea of technology developed within the COURSE50 project [6]
Rys. 5b. Idea technologii rozwijanej w ramach projektu COURSE50 [6]

be used as a carbon substitute for carburising the bath. Raw biomass or low-grade biomass char can also be used as a slag frother, with simultaneous use of post-combustion of CO produced and contained in process gases to improve the economic calculation (example of the project: GRINEAF and GREENEAF2 [8].

The increased use of steel scrap in both the integrated BF-BOF process and the electric process (EAF) of steelmaking requires rationalisation of the batch – scrap management by:

- improvement of scrap collection, which requires the use of low-quality scrap in the steelmaking process,
- recycling of Fe from by-products (slag, dust, etc.).

The use of low quality scrap for electric furnaces has a number of implications, such as:

- the need for iron additions from direct reduction in the form of DRI (direct reduced iron) or HBI (hot briquetted iron) to obtain the required steel quality levels and optimise energy consumption – FLEXCHARGE [7]; improving the productivity and energy efficiency of the electrical process requires modern online control systems,
- structural changes of furnaces enabling, among others:
  - loading with one hopper – increasing the capacity and shape of the furnace boiler as well as increasing the size of the furnace shaft,
  - loading of various types of iron-bearing charge materials – enabling operation on a diverse range of charge,
  - increasing the share of chemical energy in the process – additional supply of chemical energy (lances, burners),
- scrap heating,
- computer control of scrap loading and process management.

Another method of reducing CO_2 emissions is its **capture from process gases and storage (CCS) or use (CCUS)**. Storage called sequestration can be carried out:

- underground in natural storages such as salt caves or voids after oil extraction,
- deep below the water surface in seas and oceans,
- or in mineral deposits by binding into carbonates.

It is much more beneficial to **capture and use CO_2** (CCUS) on site to produce valuable products such as: fuels, basic chemicals, polymers or minerals, including: methanol (CH_3OH), ethanol (C_2H_5OH), 1,6-hexanediol (HDO: $C_6H_{14}O_2$), formic acid (CH_2O_2), formaldehyde (CH_2O), urea (CH_4N_2O), carbon monoxide (CO), CH_4 methane, polymers, etc. The type of product depends on the biological or chemical technology used.

2.2. CARBON-FREE TECHNOLOGIES

Realisation of such a scenario requires the development and implementation of new processes for the production of steel from virgin iron ores without the release of carbon dioxide by using hydrogen as a reducing agent and fuel. The electricity necessary for these processes is to come from renewable sources. These can be two-stage or one-stage processes.

2.2.1. Processes using hydrogen as a reducing agent and energy carrier

Both solid and liquid iron oxide reduction technologies are being developed. The two-step process is similar to the current integrated process, with the first step being the direct reduction of iron ores in lump or pellet form, using hydrogen (H_2) as reducing agent (H-DR). The use of hydrogen accelerates the reduction process (compared to the use of coke as a reducing agent), however, it is an endothermic process and additional heat is required. Additional heat can be obtained by burning H_2 or using electricity. Both the hydrogen and the necessary energy for the reduction stage will come from renewable sources. The product of the H-DR process is sponge iron or hot briquetted iron (HBI). The following equation presents the hematite ore reduction reaction (iron oxide in the third oxidation state):

$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O \tag{1}$$

The second stage of the process is the smelting of steel in an electric arc furnace (EAF) using electricity from renewable sources.

An example of a metallurgical process using hydrogen for solid state reduction is the HYBRIT technology. It includes the production of steel by processing iron from direct reduction with the use of hydrogen, and further smelting of steel in an electric arc furnace (DRP – direct reduction process / EAF).

Specially prepared iron ore lumps are reduced with solid hydrogen at a lower temperature than in the blast furnace process, resulting in an intermediate product in the form of sponge iron (DRI). The resulting steam can be condensed and the water purified before being reused in the plant. The hydrogen used in the process is produced as a result of water electrolysis, using renewable electricity (e.g. from hydro or wind power plants), and the by-product is oxygen. The storage of hydrogen in the right amount is used to balance the direct reduction process and the power grid, which allows for occasional generation of a significant amount of energy using wind or solar power plants. Sponge iron can be used as hot DRI and directly melted in an electric arc furnace (EAF) together with recycled scrap. DRI can also be processed into hot briquetted iron (HBI) which can be stored and shipped to another steel mill.

It is assumed that thanks to this process, CO_2 emissions will be reduced from 1600 kg/ton of raw steel to approximately 25 kg/ton of raw steel, i.e. by 95 % compared to the current technology used in BF / BOF integrated mills.

Comparison of the current steelmaking technology in the BF/BOF integrated process and the future HYBRIT process is shown schematically in Fig. 6.

Another example of steel production by processing iron from direct reduction with the use of hydrogen in an electric arc furnace DRP / EAF is the **SALCOS** process developed at the Salzgitter steelworks. The idea concerns the expansion of the existing steelworks with an additional hydrogen installation. In order to reduce approximately 8 million tons of CO_2 generated annually in the existing technological process, a special production process has been developed, including:

- production of hydrogen in a steam electrolyser, which is a demonstration installation with a capacity of several megawatts,
- production of electricity to power an on-site electrolyser from wind power.

Iron ore is initially reduced to iron using natural gas and additional hydrogen in a direct reduction reactor. The reaction takes place at 950 °C and produces sponge iron. Based on this method, iron reduction of up to 85 % can be achieved. The gas introduced into the reactor reduces the charge. Then, after separating the water resulting from the reduction, the remaining gas is cleaned of residual CO_2 and reused. The challenge inherent in direct reduction is integrating the new facilities into the existing steelworks. Thanks to the gradual implementation of this type of reactor, it is theoretically possible to reduce CO_2 emissions by up to 50 %. If in the future it is possible to switch all production to a direct reduction plant, this figure could be increased up to 85 %. Fig. 7 shows a comparison of the existing technology (BF/BOF) with the concept of the new technology (DRP/EAF).

The Salzgitter plant is equipped with the largest reversible high-temperature electrolyser in the world today, which performs the electrolysis process with the highest electrical efficiency. In the used technology, hydrogen is obtained from steam, industrially produced using waste heat.

One-step processes include technologies for the direct conversion of iron oxides into liquid steel. An example of such technology is direct reduction in the liquid state using hydrogen plasma (ionised hydrogen H^+) – hydrogen plasma smelting reduction, abbreviated as HPSR [4]. The raw material for this process is iron ore concentrate, and the product is liquid crude steel.

The reduction reaction in the liquid state of hematite ore using hydrogen plasma is represented by the following formula:

$$Fe_2O_3 + 6H^+ + 6e^- \rightarrow 2Fe + 3H_2O \tag{2}$$

The development of hydrogen-based technologies plays an essential role on the road map to achieving the goal of zero CO_2 emissions, however, hydrogen technologies have a long way to go. There are no definitive solutions as of today, despite many efforts in this direction.

The CO_2 reduction potential of the different technologies is as follows:

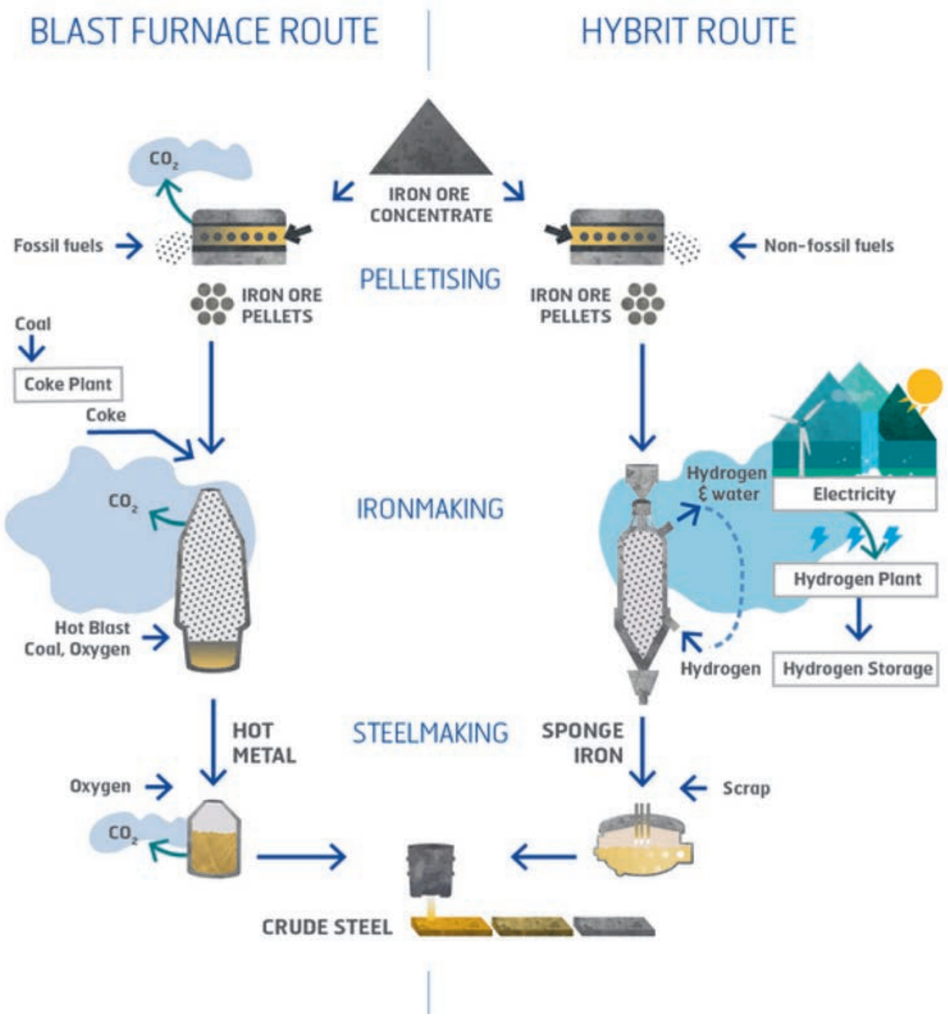

Fig. 6. Comparison of the current steelmaking technology in the integrated BF / BOF process and the future HYBRIT process [9]

Rys. 6. Porównanie obecnej technologii wytwarzania stali w procesie zintegrowanym BF/BOF i przyszłym procesie HYBRIT [9]

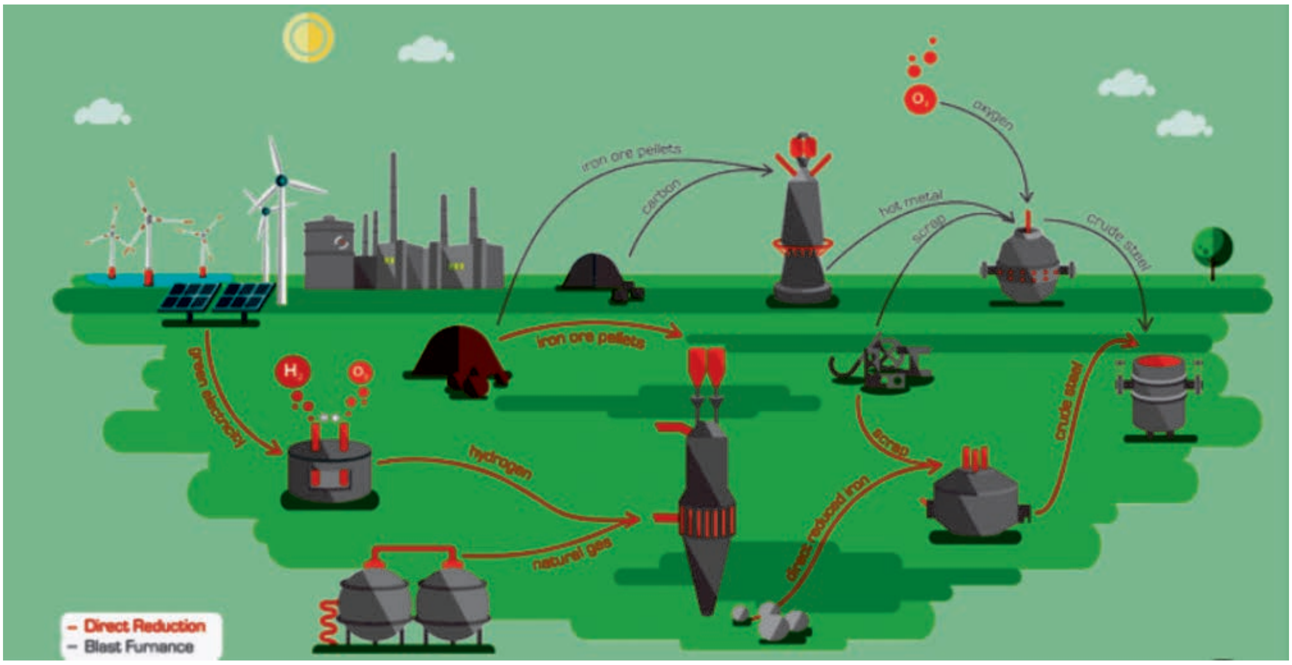

Fig. 7. Comparison of the current technology used in integrated steelworks with the future technology tested at the Salzgiter steelworks [10]

Rys. 7. Porównanie obecnej technologii stosowanej w hutach zintegrowanych z przyszłościową technologią badaną w hucie Salzgiter [10]

- 100 % BF/BOF (reference technology),
- 62 % DRI (CH_4)/EAF (400 g CO_2/kWh of energy),
- < 20 % EAF scrap (depending on the share of CO_2 related to the production of the necessary electricity),
- < 20 % DRI (H_2)/EAF (depending on the share of CO_2 related to the production of the necessary electricity),
- < 20 % liquid reduction with H_2 plasma (depending on the share of CO_2 related to the production of the necessary electricity).

The last three technologies are methods of steel production envisaged after 2050.

CO_2 emissions related to electricity production in the EU reach up to 400 g/kWh depending on the generation technology.

2.2.2. Electrolytic processes of obtaining iron

Another way to produce iron and steel with direct avoidance of CO_2 emissions is through electrolytic processes. At a higher level of technological advancement, currently assessed at TRL 5–6, is the electrolysis of alkaline iron ore at low temperature and further smelting of steel in EAF – a two-stage process.

The raw material in this process is crushed and leached iron ore and raw materials in the form of by-products and waste from non-ferrous metallurgy processes. The product of alkali electrolysis of iron ore is iron plate. This type of electrolysis is represented by the following reaction equation:

$$\tfrac{1}{2}\,Fe_2O_3 \rightarrow Fe + \tfrac{3}{4}\,O_2 \qquad (3)$$

The direct (one-stage) process of converting iron oxides into liquid steel takes place using high-temperature electrolysis of molten oxide (MOE). In this case, the raw material is lump ore and/or iron ore lumps. The product of this technology is liquid steel. The reaction of the process is described by equation (3).

The GREENSTEEL project involved a compilation of four promising technological pathways to achieve climate-neutral steel production from the above-mentioned low-CO_2 emission techniques, and then selection of roadmaps outlining the development process and research needs on a timeline.

3. TECHNOLOGICAL PATHWAYS FOR ACHIEVING CLIMATE-NEUTRAL STEEL PRODUCTION

The first technological pathway is based on conventional integrated plants (BF-BOF; blast furnace, oxygen converter), with the use of a number of additional technologies for reducing CO_2 emissions (process integration, carbon capture and use). This solution is considered short-term, which will then be replaced by target solutions (Fig. 8).

Under pathway 1 “Optimised integrated BF-BOF process”, the following key technological modifications were distinguished:

- use of alternative carbon sources – ACS (1A),
- CO_2 capture and its utilisation or sequestration – CCUS (1B),
- other activities – OA (1C).

The second technological pathway (Fig. 9) uses direct reduction with natural gas (path 2A) or hydrogen (2B), applying new methods of iron and steel production.

The third technological pathway (Fig. 10) includes technologies using liquid reduction. Two options have been distinguished, the first of which consists in reduction in an iron bath reactor, replacing the previous stage of pig iron production in BF, or reduction in hydrogen plasma, which enables the direct conversion of iron ore into liquid steel.

The fourth technological pathway (Fig. 11) uses the electrolysis of iron ore, with two promising methods of electrowinning of iron:

- low-temperature electrolysis of alkaline iron oxides,
- high-temperature electrolysis of molten iron oxide, directly producing metal in the liquid state from the oxide charge.

4. POSSIBLE SCENARIOS OF DECARBONISATION OF THE STEEL INDUSTRY

In the final stage of the GREENSTEEL project, 3 variants of possible scenarios for the decarbonisation of the steel industry were developed using individual technological pathways until 2030 and 2050. When determining them, important factors were taken into account, including the availability of resources and infrastructure, technology maturity, specific conditions in a given site, production costs and legal framework.

The proposed scenarios focus on the production of primary steel (BF-BOF), as it is responsible for around 87 % of the current CO_2 emissions of the European steel industry, making this steelmaking process a huge potential for climate change mitigation. Therefore, the requirements for enabling and starting this technological leap in the production of primary steel are assessed as the most urgent.

The analyses also take into account aspects related to the production of secondary steel (scrap-based electrical steelworks). The most important condition necessary to reduce CO_2 emissions in the production of secondary steel is the availability of the required amount of electricity from renewable sources at competitive prices.

Based on the analyses carried out, it was assumed that the optimised pathways based on the BF-BOF integrated process (pathways: 1A/B/C) and based on direct reduction (paths: 2A/B) will reach TRL 9 in the years 2030–2035 and their industrial implementation will begin, while liquid reduction (pathway 3) and iron ore electrolysis (pathway 4) may become options for later industrial implementation by 2050.

The proposed scenarios for the decarbonisation of the steel industry are graphically presented in (Fig. 12–17), with:

- pie charts showing the share of each technological pathway in the total steel production,
- bars in the upper right corner showing the share of hydrogen (H_2) and natural gas (NG) in energy consumption,
- bars in the lower right corner showing the share of alternative carbon sources (ACS) and the share of CO_2 capture, utilisation and storage techniques (CCUS),
- and bars in the middle representing the potential of each pathway to reduce CO_2 emissions.

The first scenario for 2030 (Fig. 12), assuming "mixed implementation" of decarbonisation technologies, was proposed with the following assumptions:

- at least 46 % of the production capacity of primary steel in EU-27 will not be subject to significant technological changes until 2030,
- the remaining 54 % (i.e. with upcoming changes in BF technology) are assigned to four groups of national and/or regional framework conditions,
- as for all scenarios, the total annual steel production capacity in EU-27 is assumed to remain constant at 160 million tons per year.

This 2030 scenario assumes that 56 % of production will be subject to gradual improvement of the BF-BOF pathway through other activities (OA – pathway 1C), 22 % of production capacity will use alternative carbon sources and/or CCUS techniques, and the remaining 22 % of production will be covered by direct reduction (pathway 2), with an average share of hydrogen of 9 %. Such a solution would make it possible to achieve the decarbonisation goals set by the EU by 2030 (reducing CO_2 emissions by 25 % compared to 2015).

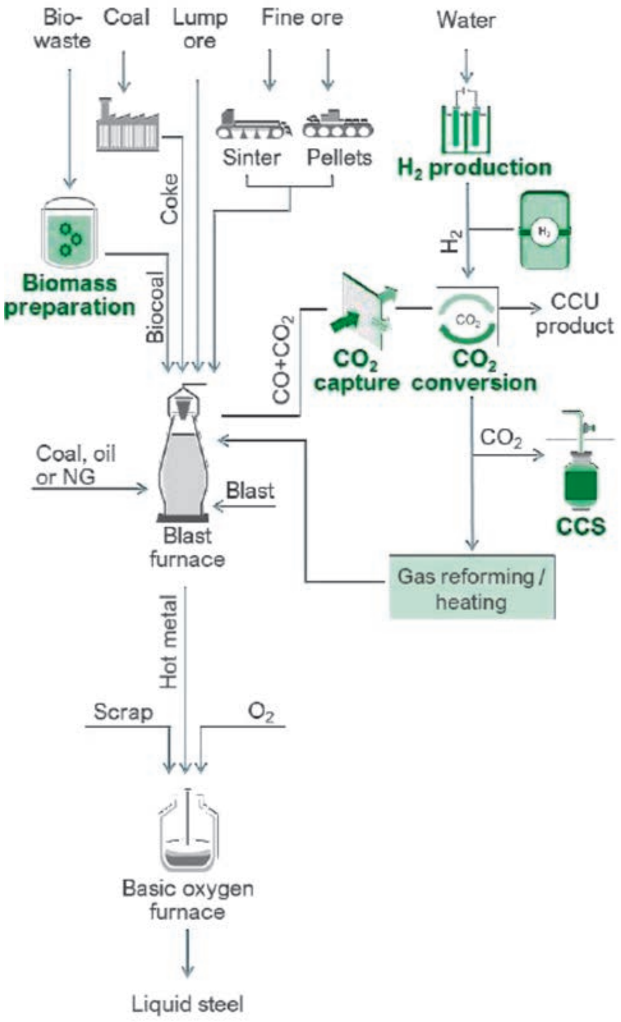

Fig. 8. Route 1 – Based on the conventional BF-BOF system – optimised BF-BOF technology [2]

Rys. 8. Ścieżka nr 1 – Oparta na konwencjonalnym układzie BF-BOF – zoptymalizowana technologia BF-BOF [2]

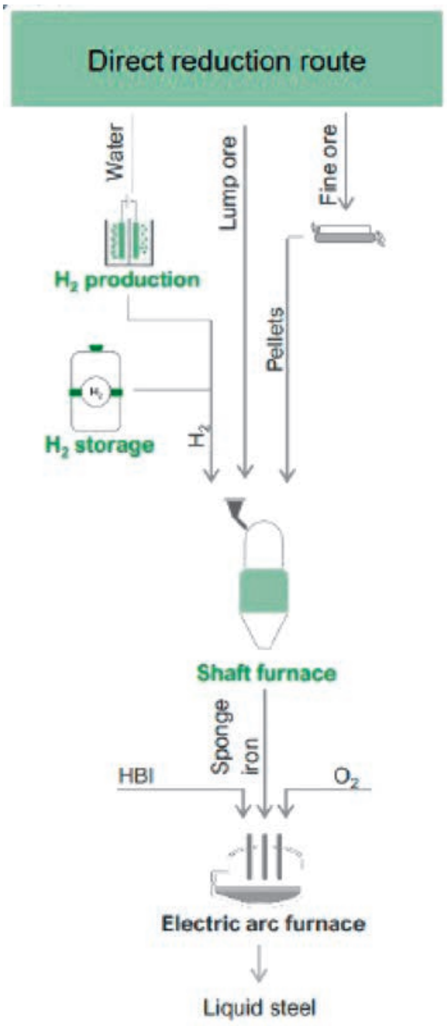

Fig. 9. Route 2 – direct reduction [2]

Rys. 9. Ścieżka 2 – redukcja bezpośrednia w stanie stałym [2]

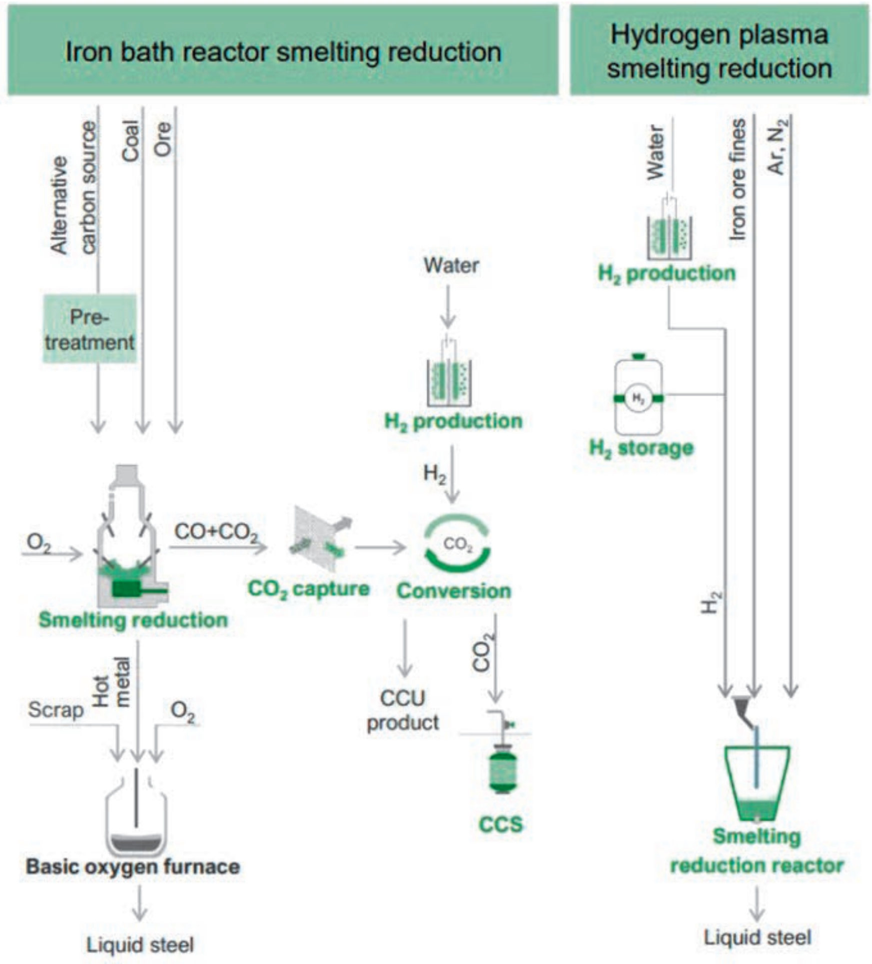

Fig. 10. Route 3 – smelting reduction routes [2]

Rys.10. Ścieżka nr 3 – procesy redukcji w stanie ciekłym [2]

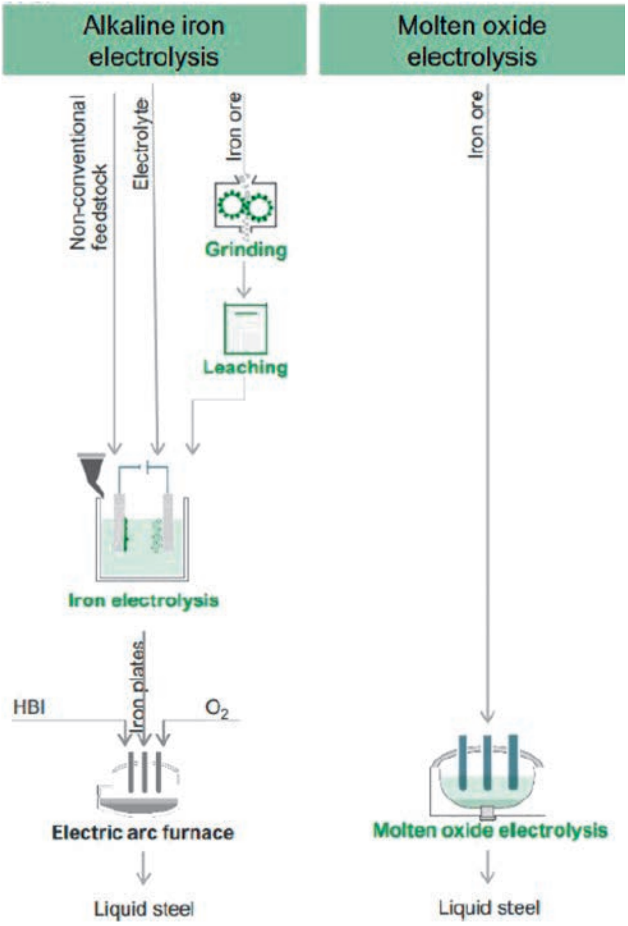

Fig. 11. Route 4 – electrolytic methods of obtaining iron and/or steel [2]

Rys.11. Ścieżka nr 4 – elektrolityczne metody otrzymywania żelaza i/lub stali [2]

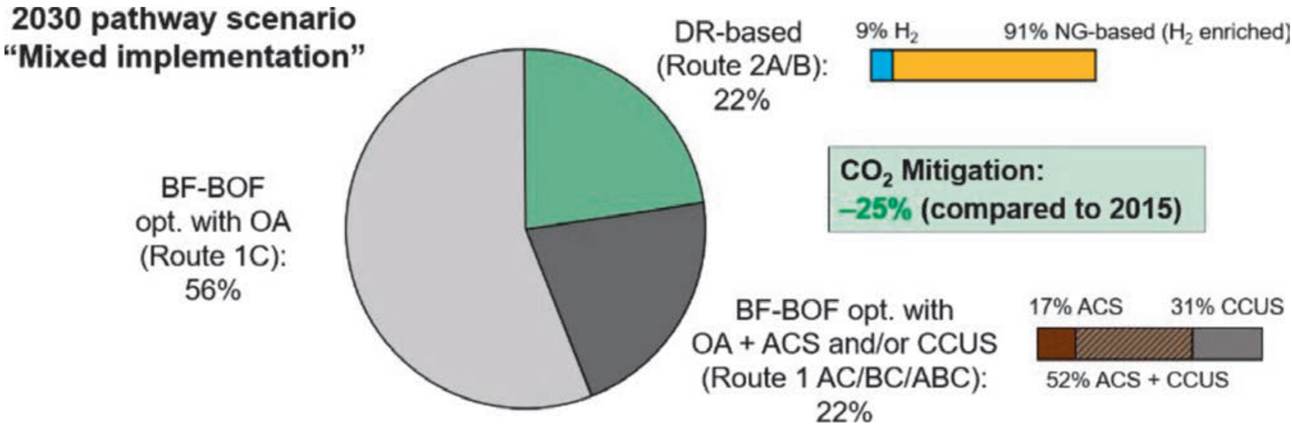

Fig. 12. Scenario of steel industry decarbonisation by 2030 "Mixed implementation" [2]

Rys. 12. Scenariusz dekarbonizacji przemysłu stalowego do 2030 „Wdrożenie mieszane"[2]

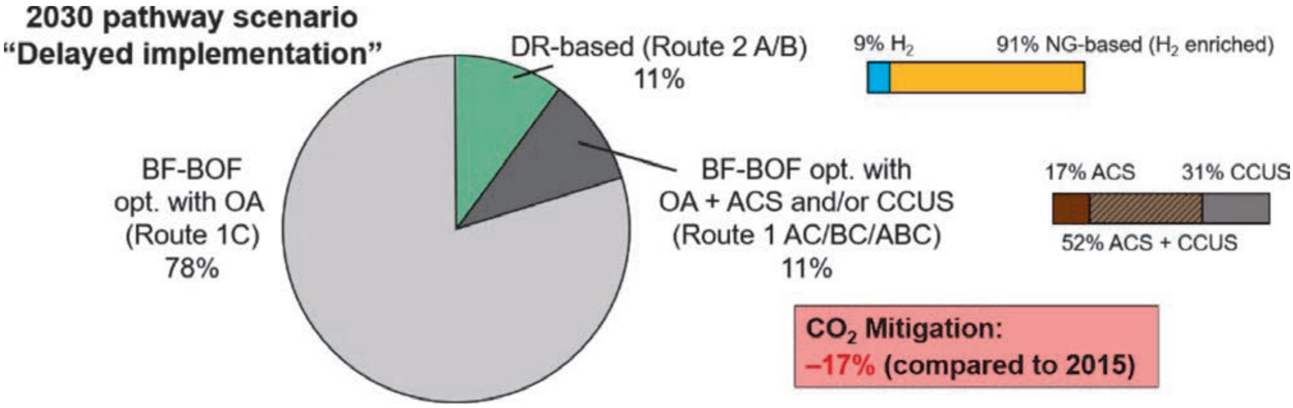

Fig. 13. Scenario of steel industry decarbonisation by 2030 "Delayed implementation" [2]

Rys. 13. Scenariusz dekarbonizacji przemysłu stalowego do 2030 „Opóźnione wdrożenie" [2]

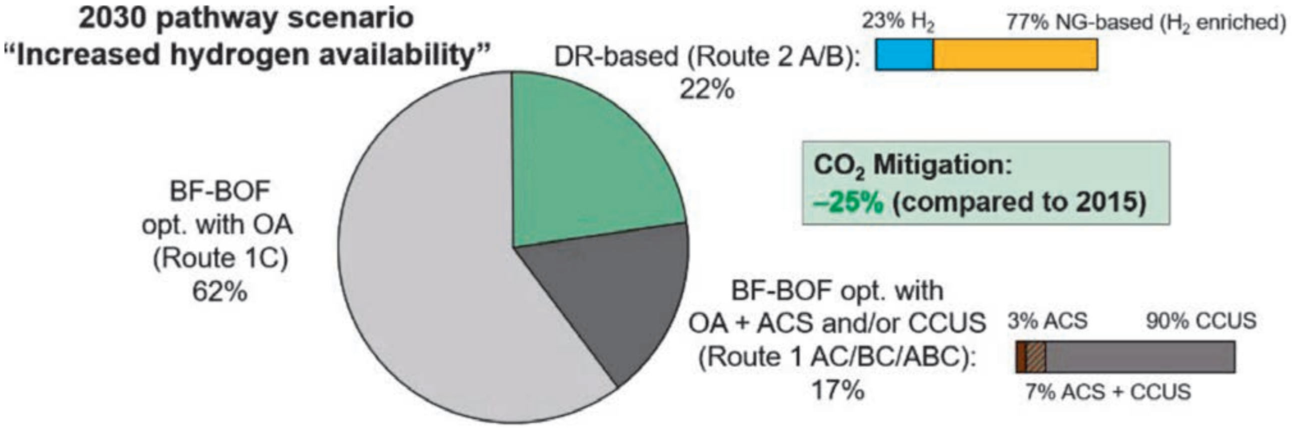

Fig. 14. Scenario of steel industry decarbonisation by 2030 "Increased hydrogen availability" [2]

Rys. 14. Scenariusz dekarbonizacji przemysłu stalowego do 2030 „Zwiększona dostępność wodoru" [2]

Another scenario for 2030 (Fig. 13) called "Delayed Implementation" assumes that 50 % of major technology changes based on alternative carbon sources, CCUS or direct reduction will be delayed and implemented after 2030. As a result, 78 % of primary steel production is only incrementally improved under "Other Activities" (pathway 1C), 11 % will include alternative carbon and/or CCUS technologies, and a further 11 % will switch to direct reduction production. This scenario enables a 17 % reduction in CO_2 compared to 2015.

The third scenario for 2030 (Fig. 14), called "Increased Availability of Hydrogen", takes into account the wider use of hydrogen in the steel industry (+0.2 million tons, i.e. +25 %). In the absence of certainty of the availability of alternative coal sources in 2030,

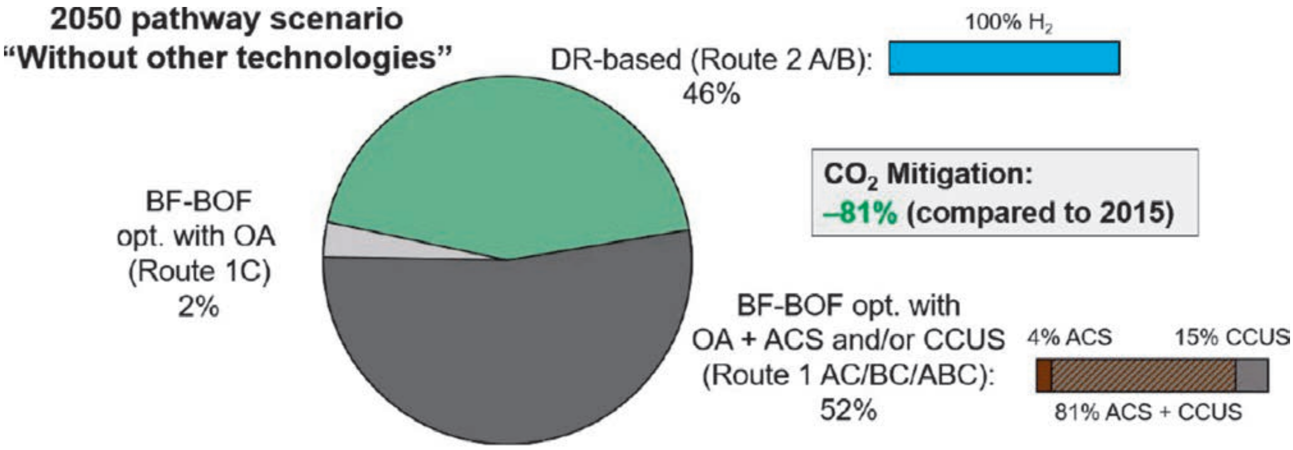

Fig. 15. Scenario of steel industry decarbonisation by 2050 "Without other technologies"[2]
Rys. 15. Scenariusz dekarbonizacji przemysłu stalowego do 2050 „Bez innych technologii"[2]

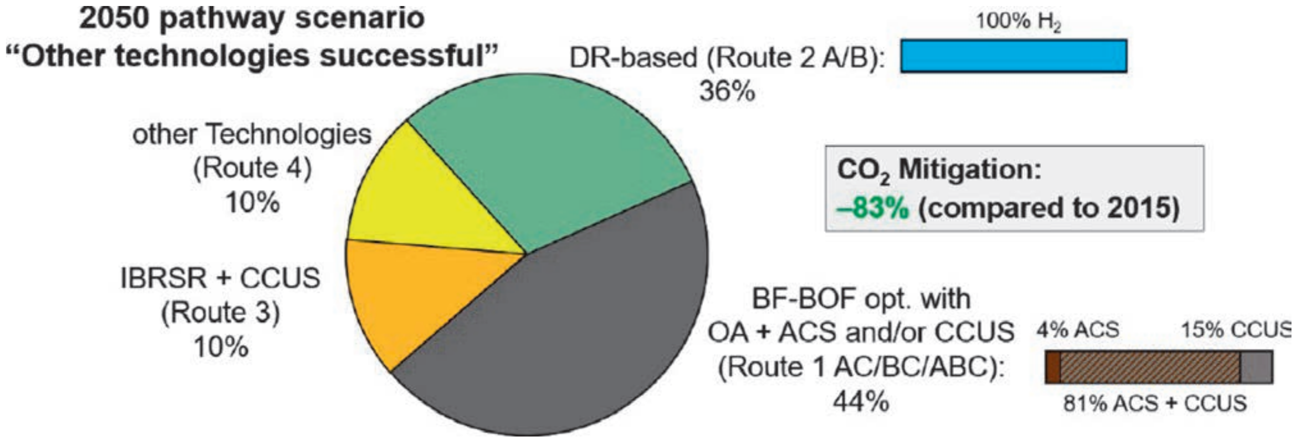

Fig. 16. Scenario of steel industry decarbonisation by 2050 "Other technologies successful" [2]
Rys. 16. Scenariusz dekarbonizacji przemysłu stalowego do 2050 „Inne technologie zakończone sukcesem" [2]

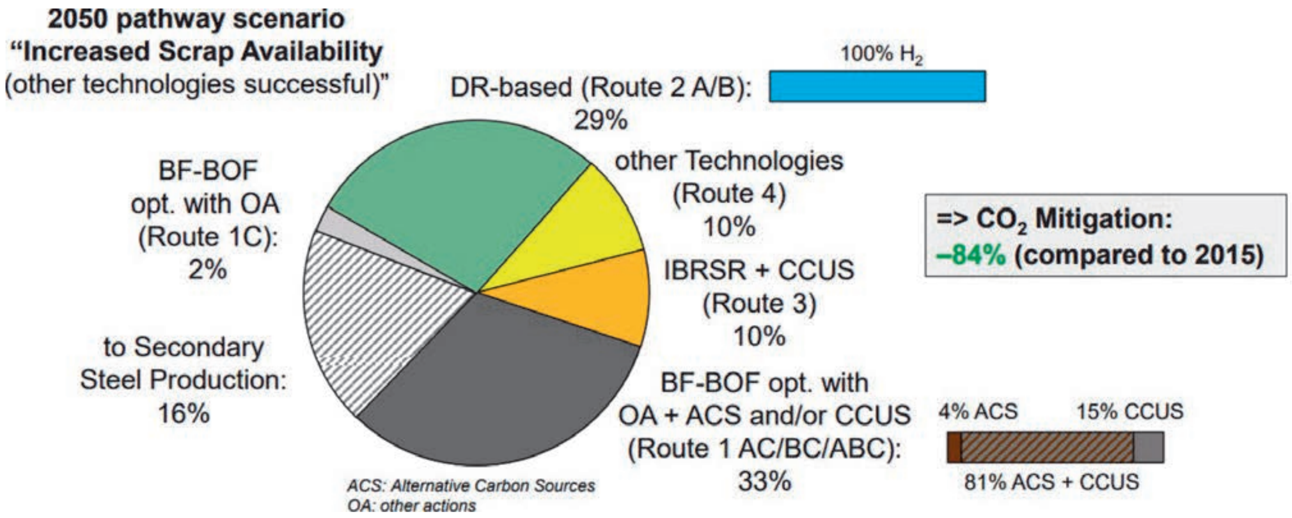

Fig. 17. Scenario of steel industry decarbonisation by 2050 "Increased scrap availability" [2]
Rys. 17. Scenariusz dekarbonizacji przemysłu stalowego do 2050 „Zwiększona dostępność złomu" [2]

its lower consumption was assumed. The CO_2 savings were enhanced by using the optimised BF-BOF process pathway through "other means" (pathway 1C) and direct reduction production (pathway 2). This scenario requires a significant change of 39 % of primary steel production capacity (compared to 44 % in the "mixed implementation" scenario). It meets the EU target of reducing CO_2 emissions by 25 % compared to 2015, and thus represents an alternative way to achieve this target, focused on hydrogen.

All three scenarios for 2050 meet the goal of reducing CO_2 emissions by >80 % using different technologies.

The 2050 “No Other Technologies” scenario (Fig. 15) is an extrapolation of the “Mixed Implementation” scenario from 2030 to 2050. It assumes that by 2050 no other breakthrough decarbonisation technology will be industrially successful, so the decarbonisation process must be based on the use of alternative carbon sources, CCUS techniques and hydrogen-based direct reduction. In this scenario, 46 % of primary steel production is covered by direct reduction processes using 100 % hydrogen, 52 % is covered by the BF-BOF process enhanced with significant alternative carbon sources and/or the use of CCUS (pathways 1A and 1B). However, only 2 % of BF-BOF production capacity is undergoing incremental improvements. Such a division of technologies would lead to an 81 % reduction in CO_2 emissions compared to 2015, thus creating a solid basis for achieving the EU’s goal of climate neutrality.

The authors of [2] entitled the next scenario for 2050 “Other Successful Technologies” (Fig. 16), where it is assumed that two additional technological pathways of decarbonisation will be implemented industrially: smelting in reactors with an iron bath using CCUS techniques (pathway 3) and other technologies, such as iron ore electrolysis (pathway 4) with their share of 10 % each. 36 % of production capacity would be subject to hydrogen-based direct reduction. The remaining 44 % of primary steel production will be covered using pathway 1, a modified BF-BOF process with significant use of alternative carbon sources (pathway 1A) and CCUS (pathway 1B). As a result, the reduction of CO_2 emissions compared to 2015 could be up to 83 %.

The scenario for 2050, taking into account the increased availability of scrap (Fig. 17), assumes a partial shift of production capacity for primary steel to the production of secondary steel. In this scenario, it is set at 15 million tons out of 160 million tons of annual production. The distribution of the remaining primary steel capacity includes the two remaining scenarios for 2050 where other technologies either succeeded or failed. Both cases lead to a slight increase in CO_2 emission reduction to 84 % compared to 2015.

4. SUMMARY

EU countries, similarly to other developed countries in the world, are preparing for a technological revolution in iron and steel metallurgy, involving the maximum reduction of CO_2 emissions as a result of eliminating as much coal as a reducing and energy agent as possible. The European Commission has set itself two stages of this transformation:

- First – transitional, planned until 2030, consisting in the modification of existing technologies in terms of reducing CO_2 emissions by 50 % compared to 1990,
- Second – consisting in achieving climate neutrality of the steel industry in Europe by 2050 (reduction of CO_2 emissions by about 84 % compared to 2015) as a result of:
  - elimination of fossil coal from metallurgical process,
  - use of green hydrogen,
  - implementation of direct reduction processes using hydrogen,
  - maximising the share of electric process of producing steel from scrap and iron from direct reduction; furnaces powered by renewable energy,
  - application of CO_2 capturing and storage as well as capturing and utilisation processes,
  - production of iron by electrolysis,
  - use of electricity of renewable sources, etc.

Achieving these goals will be a costly and lengthy process. Strategic political decisions are necessary, as well as co-financing of R&D works, implementations and investment processes, by the governments of individual countries, the European Union, and the steel producers themselves.

One of the EU-funded projects was the GREENSTEEL project. A consortium of implementers composed of ten partners from EU countries defined promising decarbonisation technologies, defined technological paths constituting chains of processes composed of these technologies, as well as medium- and long-term (until 2030 and 2050) scenarios of decarbonisation of the steel industry, which are briefly quoted in in this article as part of the dissemination of the project results. When developing the scenarios, a number of important factors were taken into account – barriers: technological, economic, social and legal, including: availability of resources and infrastructure, maturity of technology, specific conditions in given countries, production costs, etc. The above aspects will be presented in subsequent articles.

The assumed dates for the implementation of climate goals may be extended due to possible unpredictable factors in the environment, such as the COVID pandemic, Russia’s attack on Ukraine and the ensuing energy crisis.

REFERENCES

[1] F. Cirilli, G. Stubbe, T. Overbeck, J. Borlée, J.-Ch. Pierret, M. Draxler, A. Sormann, Ch. Wang, T. Lundberg, H. Granbom. CO_2 mitigation in Electric Arc Furnace steelmaking. In: Workshop: *GreenSteel by EAF route: a sustainable value in the EU Circular Economy scenario*. Bergamo, Italy, 13–14 November 2019.

[2] Climate-neutral Steelmaking in Europe, Decarburisation pathways – Investment needs – Policy Conditions – Recommendations. European Research Executive Agency (REA), Research Fund for Coal and Steel RFCS, 2022. [Online] Available at: https://op.europa.eu/en/publication-detail/-/publication/89cda1b2-b169-11ec-83e1-01aa75ed71a1/language-en/format-PDF/source-254269180

[3] M. Draxler, A. Sormann, T. Kempken, T. Hauck, J.-Ch. Pierret, J. Borlee, A. Di Donato, M. De Santis, Ch. Wang. GreenSteel for Europe, Technology Assessment and Roadmapping. March 2021. [Online] Available at: https://www.estep.eu/assets/Uploads/D1.2-Technology-Assessment-and-Roadmapping.pdf

[4] HISARNA Building a sustainable steel industry. [Online] Available at: https://www.tatasteeleurope.com/sites/default/files/tata-steel-europe-factsheet-hisarna.pdf

[5] COURSE 50 Innovation Challenges [Online] Available at: https://www.challenge-zero.jp/en/casestudy/549

[6] COURSE 50 Technology. [Online] Available at: https://www.course50.com/en/technology/

[7] [Online] Available at: https://cordis.europa.eu/project/id/RFSR-CT-2005-00001/pl.

[8] F. Cirilli, D. Mirabile, L. Bianco, G. Baracchini, T. Rekersdrees, M. Marcos, H. Sommerauer, T. Griessacher, T. Echterhof, T. Reichel. *Biochar for a sustainable EAF steel production (GREENEAF2). Final Report.* Research and Innovation. EUR 29517 EN, 2018. [Online] Available at: https://www.researchgate.net/publication/334625171_Biochar_for_a_sustainable_EAF_steel_production_GREENEAF2

[9] M. Pei, M. Petäjäniemi, A. Regnell, O. Wijk. Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland. *Metals*, 2020, 10(7), pp. 972-982. doi: 10.3390/met10070972

[10] Scientific support for the transformation of the steelworks – Salzgitter Flachstahl GmbH in cooperation with TU Clausthal [Online] Available at: https://www.salzgitter-ag.com/en/newsroom/press-releases/details/salzgitter-flachstahl-in-cooperation-with-tu-clausthal-19462.html