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Advancements in Transition to Green Steel in Europe through Direct Reduced Iron Production

Postępy w przejściu na zieloną stal w Europie poprzez produkcję żelaza gąbczastego

Abstract: This article describes the current situation in Europe regarding methods of steel production and transition to green steel, produced in a sustainable way, i.e. with renewable energy and without fossil fuels, in order to reduce greenhouse gas emissions. The study focuses on direct reduction (DR) as potentially the best technology to eliminate the use of fossil fuels in the steel industry. The main commercial processes of direct reduced iron (DRI) production such as MIDREX, Energiron, PERED, SL/RN, Fastmet and Circored are described and compared in terms of the quality of finished products, operational conditions and efficiency. The article presents recent statistics regarding the production capacity of DRI, comparing Europe with the rest of the world. Plans concerning the construction of DRI plants across Europe are summarised alongside other projects aimed to support the process of transition to green steel by providing environmentally friendly materials or increasing efficiency of already implemented technologies by recycling waste materials.

Key words: direct reduced iron, direct reduction, green steel, greenhouse gases emissions, steel production in Europe

Streszczenie: Niniejszy artykuł opisuje obecną sytuację w Europie w zakresie metod produkcji stali i przejścia na zieloną stal w celu zmniejszenia emisji gazów cieplarnianych. Koncentruje się na bezpośredniej redukcji (DR) jako potencjalnie najlepszej technologii eliminującej zużycie paliw kopalnych w przemyśle stalowym. Główne komercyjne procesy produkcji bezpośrednio redukowanego żelaza (DRI), takie jak MIDREX, Energiron, PERED, SL/RN, Fastmet i Circored, zostały opisane i porównane pod względem jakości produktu końcowego, warunków operacyjnych i wydajności. Przedstawiono najnowsze statystyki dotyczące zdolności produkcyjnych DRI, porównując Europę i resztę świata. Ogłoszone plany budowy zakładów DRI w całej Europie zostały podsumowane wraz z innymi projektami, które mają na celu pomoc w przejściu na zieloną stal poprzez dostarczanie materiałów przyjaznych dla środowiska lub zwiększenie wydajności już wdrożonych technologii poprzez recykling materiałów odpadowych.

Słowa kluczowe: żelazo gąbczaste, redukcja bezpośrednia, zielona stal, emisja gazów cieplarnianych, produkcja stali w Europie

1. Introduction

The last several centuries in Europe have seen the dominant route for steel production based on the blast furnace (BF) – basic oxygen furnace (BOF). The process is heavily dependent on fossil fuels, such as coal, natural gas and, sometimes, oil, as reducers of iron ore and energy sources. Direct and indirect CO_2 emissions from the BF-BOF process reach, on average, 2.2 t of CO_2 per 1 t of crude steel [1]. The BF-BOF route is also responsible for the significant amount of air pollutant emissions, originating mainly in coke and sinter plants, required for the preparation of raw materials for blast furnaces. Presently, approximately 56.3% of steel in the European Union is produced using the BF-BOF route, whereas the remaining 43.7 % is produced in electric arc furnaces (EAF) with scrap as the main feedstock. Producing steel in EAFs can result in significantly lower CO_2 emissions (0.3 t per 1 t of crude steel [1]), yet it heavily relies on power plants responsible for carbon emissions. This route is also dependent on the availability and quality of scrap (especially related to a copper content and its variability), which may decrease the quality of the finished product. On its own, the above-named route cannot replace the BF-BOF process entirely as there is greater demand for new steel than available recyclable scrap. In 2022, the world steel production reached 1885 Mt, 136.3 Mt of which were produced in the European Union [2]. Due to increasing urgency in dealing with the climate change crisis and in order to meet the targets of the Paris Agreement, the carbon emission of the European steel industry (as of 2022 reaching 221 Mt of greenhouse gas emissions annually, 5.7 % of the total EU emission [3]) must be reduced. To achieve this goal, the production should be transitioned to green steel, i.e. steel produced in a sustainable and environmentally friendly way, with the use of renewable energy sources and without fossil fuels, combined with the reduction of greenhouse gas emissions and recycling waste products.

One of the available solutions consists in increasing the use of alternative ironmaking techniques, primarily involving direct reduced iron (DRI), also referred to as sponge

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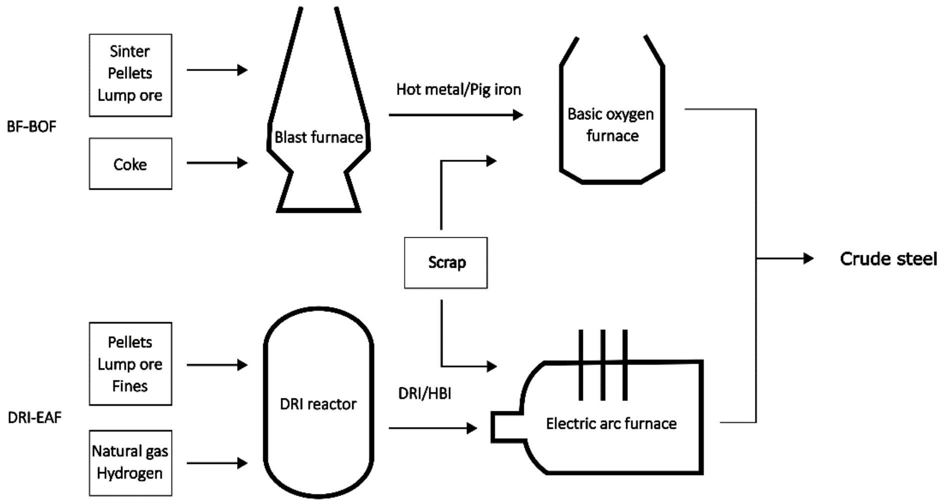

Fig. 1. Comparison of BF-BOF and DRI-EAF route, own elaboration based on [5]

iron. The direct reduction process involves reduction in the solid phase using natural gas, coal or hydrogen as a reducing agent. Unlike the BF-BOF process, the DRI-EAF (Fig. 1) route allows the greater use of renewable energy sources and the replacement of fossil fuels with green hydrogen as a reducer. Unfortunately, most of the current DRI production in the world is still based on fossil fuels (coal and natural gas) as reducing agents. However, average carbon dioxide emissions (1.4 t per 1 t of crude steel [1]) are still significantly lower than those resulting from the use of the BF-BOF route. Fig. 1 presents the flow chart of the steel production route. The potential of this technology to greatly limit the carbon emission of the steel industry, i.e. by up to 80–90 % on a long-term basis [4], has inspired several major European steel producers to fund projects including DRI installations.

2. Commercial methods of sponge iron production

Presently, there are 4 major categories of commercially viable processes of DRI production based on types of reactors, i.e. shaft furnace, fluidized bed, rotary kiln and rotary hearth. In addition, there are many technological implementations of these reactors provided by numerous companies around the world. These implementations differ, among others, in terms of iron source, fuel used for the reduction of iron ore, types of DRI produced, carbon contents in the finished product and plant capacity. The use of a given system is primarily influenced by economic factors and types of other steelworks installations or the possibility of transporting finished products. Direct reduced iron (DRI) can be produced in three forms. Hot DRI (HDRI) is the direct product of the reduction process, with or without limited cooling. As DRI is a highly porous and reactive material, it must be kept in neutral atmosphere to mitigate the risk of uncontrolled heating from reoxidation or even spontaneous ignition. Direct reduced iron is transported at high temperature, usually exceeding 650°C, by conveyor belts or hot transport vessels to the adjacent EAF. This method enables the effective use of residual heat from the reduction process, aimed to increase productivity and reduce production costs in the next step of steel production. Cold DRI (CDRI) has the same shape/structure as the input material and is allowed to cool to nearly ambient temperature after leaving the reactor. This method is mostly used with pellets or lumps (and rarely with fine materials). Cold direct reduced iron is most commonly used onsite, in the nearby EAF, to prevent reoxidation, when hot charging is not feasible due to equipment or space constraints. Hot briquetted iron (HBI) is made from reduced fines or concentrates, which are transported still hot from the reduction process (usually in neutral atmosphere) to the briquetting machine connected to the reactor and, next, pressed into small and rectangular briquettes (allowed to cool afterwards). Hot briquetted iron is the easiest transportable form of DRI due to low reoxidation rates, high density and strength. This type of DRI is preferred in trade and can be used in the EAF, BF and BOF. Table 1 presents the comparison of different technologies of DRI production and examples of major commercial processes utilising individual reactor types. Examples of the most common DRI production processes are described in greater detail in the remainder of the article.

Table 1. Types of DRI production processes [6]

Reactor type	Shaft furnace	Rotary kiln	Rotary hearth	Fluidized bed
Iron source	Pellets/lumps	Pellets/lumps	Fines/concentrates	Fines
Typical reducing agent	Natural gas/hydrogen	Coal	Coal	Natural gas/hydrogen/ Coal
Commercial processes	MIDREX, Energiron, PERED	Davy DRC, SL/RN, Krupp-CODIR, Jindal, Siil	Fastmet, Fastmelt Inmetco, COMET, SIDCOMET	Finmet, Finex, Circored, Circofer, Fior

2.1. Shaft furnaces

2.1.1. MIDREX

MIDREX is the process most widely used in DRI production around the world. It was developed in the USA in the 1960s, where the first demonstration plant was built in Oregon Steel Mills in Portland, Oregon [7]. The process is based on a shaft furnace with an external gas reformer and a heat recovery system (Fig. 2). Iron ore, in the form of pellets or lumps, is charged and preheated in the top part of the furnace. Afterwards, when moving downwards, it is reduced using gases supplied in the middle part of the furnace. In the lower section, below gas inlets, DRI is cooled (with neutral gas) and, next, discharged from the furnace. The design of the furnace allows the continuous charging and discharging of material through ports dynamically sealed with gas.

There are two main types of the process, i.e. MIDREX NG, using natural gas, and MXCOL, using coal. In MIDREX NG, reducing gas is obtained from natural gas mixed with recycled gas from the top of the furnace, reformed using nickel as a catalyst to create hydrogen and carbon monoxide. Such a solution enables the recycling of heat in heat recovery systems and the reuse of reduction by-products, i.e. H_2O and CO_2, for lowering energy and natural gas consumption. Globally, MIDREX NG is the most common system used in the production of DRI. If natural gas is not an economically viable option, coal gasification can also be used to provide the shaft furnace with reducing gas in the MXCOL process. There are two possible options allowing the capture of carbon in the system (aimed to reduce CO_2 emissions). The first solution involves the removal of carbon dioxide from top gas used for heating in the reformer, thus enabling the separation and removal of approximately half of CO_2. The second option consists in the removal of CO_2 from flue gas of the reformer. Nearly all carbon dioxide can be removed in the above-presented manner.

Presently, there are two additional MIDREX processes under development, i.e. MIDREX Flex – using natural gas as fuel, with options to replace it partially with hydrogen (aimed to reduce greenhouse gas emissions by 65–90% if compared with emission accompanying traditional steelmaking) and MIDREX H_2, the process which is supposed to use hydrogen as its only source of reducing gas, enabling the reduction of emission by over 90% [8]. Depending on needs, various types of additional equipment can be installed on site (including a DRI cooler, briquetting machine, hot transport conveyors, vessels or HOTLINK, i.e. MIDREX proprietary HDRI transport technology), enabling the configuration of all types of processes aimed to produce any type of DRI or its combinations.

2.1.2. Energiron (previously known as HyL)

The Energiron process was developed by Tenova and Danieli. In the first generation, i.e. HyL I, developed in 1957 in Monterrey, Mexico [10], the reduction process was performed in batches in four fixed-bed retorts. The next generation, i.e. HyL II, was based on a shaft furnace reactor and was replaced with the next generation of shaft furnace systems, i.e. HyL III. Presently known as Energiron III, the process is based on a typical arrangement with external natural gas reformer, similar to that applied in the MIDREX systems. The above-named solution is used when source gas is characterised by the high concentration of heavy hydrocarbons or sulphur compounds. In a new Energiron ZR plant, reduction gases can be reformed directly in the shaft furnace. In such a solution, the external reformer is not required and energy efficiency of the process can reach 80%. Alternatively, hydrogen can be used directly as part of a reducing gas mixture, without necessitating significant modifications to the system. The direct reduction furnace operates at pressure restricted within the range of 5 bar to 8 bar, leading to higher productivity and efficiency. The combination of higher pressure with no need for the external reformer enables the more efficient use of space. The size of the system can be up to 60% smaller than that of plants providing comparable production capacity [11]. If necessary, additional modifications of the system enable the use

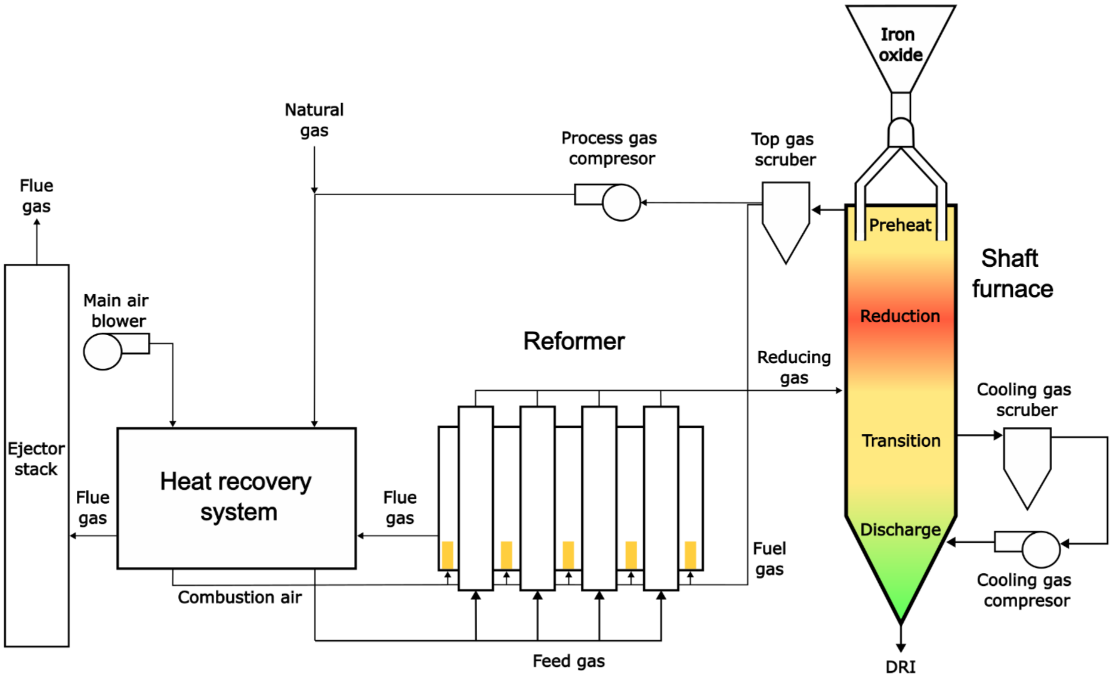

Fig. 2. Flow chart of MIDREX process, own elaboration based on [8, 9]

of gases from the gasification of coal, biomass, from the external gas reformer or coke oven gas. The plants can be adjusted to produce any type of DRI. Due to a high iron carbide (Fe_3C) content, cold DRI produced in Energiron plants can be transported without briquetting. The proprietary HYTEMP system for feeding HDRI directly to the EAF can be integrated with the furnace. The Energiron process provides the largest range of plant production capacity of DRI production methods under discussion. Currently available modules range from micro-modules having a capacity of 0.2 Mt/y, through mini-modules with a capacity of 0.5 Mt/y to custom modules having a capacity of 2.5 Mt/y. Future plans include plants able to produce up to 3 Mt of DRI per year.

2.1.3. PERED

The PERED direct reduction process was developed by Mines and Metals Engineering GmbH, and is patented both in Germany and Iran. The process is based on a vertical shaft furnace design performing the reduction of iron ore in the solid phase using reducing gases. The principle of operation of this system is similar to that of other shaft furnace technologies, yet, in comparison with competitive solutions, PERED focuses on improving energy efficiency as well as on flexibility in terms of raw materials and energy sources. One of the major differences in the furnace design includes a dedicated easy-flow device called the china hat and located in the transition zone. The solution helps adjust the uniform flow of material inside the reactor. The uninterrupted gas flow reduces iron ore and carburises it in the process; fuel consumption is reduced by recycling furnace top gas from the furnace back into the process through the heat exchanger. Furnace feedstock can consist of 100% of oxide pellets or up to 70% of lump ore and up to 10% of solid fines [12]. The PERED process is suitable for iron ore characterised by high sulphur contents. The process is compatible with natural gas reformed in the PERED reformer or a standard steam reformer. Coal can be applied as the source of reducer by using gasifier syngas, COREX offgas or coke oven gas. The foregoing allows reaching a high metallization degree of up to 95% and a carbon content of up to 3% of in DRI. PERED systems can be configured to produce HBI, CDRI, HDRI or combinations of those.

2.2. Rotary kiln – SL/RN

The SL/RN process is, in fact, the combination of two processes developed separately, i.e. the Stelco-Lurgi (SL) process for the production of DRI, developed in the 1960s and the Republic Steel-National Lead (RN) process for the beneficiation of low grade ore, developed in the 1920s. The solution is based on a rotary kiln furnace using solid phase fuels such as coal, coke, char and lignite [13]. Anthracite and coke breeze can also be used in special cases. The SL/RN process can also be used with a wide range of iron-bearing materials such as lump ore, pellets, ilmenite, beach sand and, with some system modifications, iron ore fines. The above-named possibilities make the SL/RN process one of the most adaptable in terms of fuel and charge. Dolomite and limestone are commonly used as desulfurizing agents. The basic steps of this process consist in mixing charge ingredients, the reduction of heated mixture in the rotary kiln, cooling the DRI in the rotary cooler and separating DRI from coal which has not reacted (and which is usually returned to the system and used as part of charge mixture). The system requires the constant supply of air to the furnace, whereas flue gas is cleaned in a multistep process. There are two types of the SL/RN process available. The standard SL/RN facility consists of raw material handling facilities, rotary kiln, rotary cooler, after-burning chamber, waste heat boiler, electrostatic precipitator as well as product separation and handling facilities. The system is capable of producing up to 1.6 Mt of DRI annually. The SL/RN-Xtra system also includes pelletizing facilities and pre-hardening grate, enabling the production of DRI directly from iron fines on an on-site basis (in a single installation). The SL/RN-Xtra variant can be also adapted for using anthracite and coke breeze as fuel and reducing agent. The production capacity of the aforesaid variant is higher and can reach up to 2 Mt of DRI per year [14]. Both SL/RN systems, along with other rotary kiln furnaces, are currently the most common systems used in India.

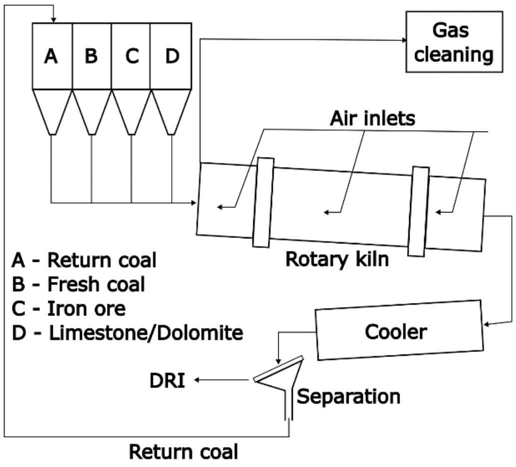

Fig. 3. Flow chart of SL/RN process, own elaboration based on [13, 15]

2.3. Rotary hearth – Fastmet

The Fastmet process was developed by Kobe Steel and MIDREX Technologies. The first pilot plant was built in 1995 at Kobe Steel's Kakogawa Works [16]. The Fastmet system consists of a feed preparation line, a rotary hearth furnace, an exhaust gas treatment and a product discharge line. The reduction of iron oxide, typically in the form of briquettes or pellets, is carried out in the solid phase with coal as a reducing agent. The feed mix is placed in one or two layers over the hearth and, afterwards, is moved through three heating zones. In each zone, burners can be configured to achieve specific combustion parameters. After between 6 and 10 minutes, the reduced material reaches the end of the process and DRI is discharged by a helical screw into a discharge system, which can be configured with coolers, a briquetting machine or containers and produce every type of DRI. An alternative version of the Fastmet process is the Fastmelt process. This type of system has all the features of the Fastmelt process and an additional line for the hot discharge of DRI to a specially designed electric iron melting furnace (EIF), producing hot metal. The Fastmet process is particularly useful for recycling steel plant metallurgical waste [16]. Because the "standard" system is already equipped with a pelletizing or briquetting machine, it is relatively easy to replace part of the iron ore in feed preparation process with iron bearing dusts such as BF, BOF or EAF. Those kinds of materials (especially the BF dust) are usually significantly contaminated with heavy metals, in particular zinc. In the Fastmet process, the issue of zinc-

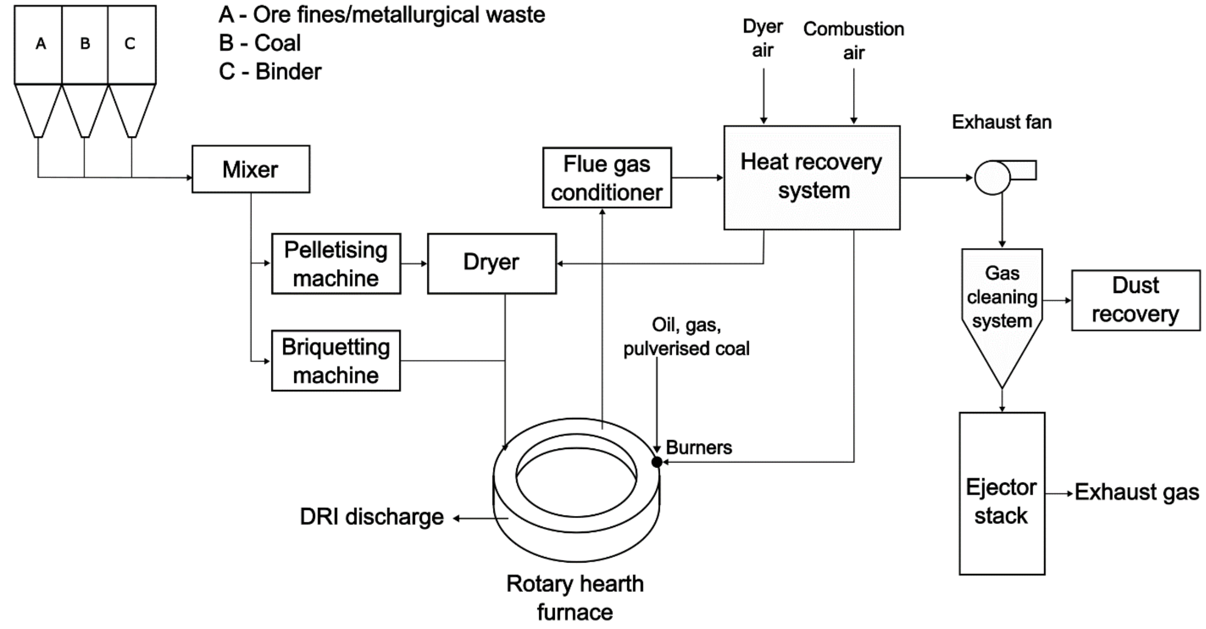

Fig. 4. Fastmet process flowchart, own elaboration based on [13, 14]

based contamination can be dealt with by using sufficiently high temperature (over 1300°C), triggering the vaporisation of zinc during the reduction process. The off-gas treatment facilities can be equipped with adequate dust collection systems enabling the separation of zinc oxide, which can subsequently be sold to zinc producers and recycled. Because of its unique usefulness in recycling waste products, Fastmet systems often accompany traditional BF-BOF plants in integrated steelworks.

2.4. Fluidized bed – Circored

The Circored process is based on a fluidized bed reactor with hydrogen used as the only reductant of iron oxide. The process was developed in the 1990s by Lurgi Metallurgie (presently Metso-Outotec). Under normal conditions, the system uses iron ore fines having a particle size restricted within the range of 0.1 mm to 2.0 mm, however, it is also possible to use particles having a size of up to 6 mm. If necessary, an additional micro-granulation step can be implemented if ultrafine (< 50 μm) ores or dusts are to be used as input material. Prepared fines are preheated to temperature restricted within the range of 850 °C to 900 °C. Afterwards, the reduction of iron oxide is performed in a two-stage process. The first stage involves the fast pre-reduction in a circulating fluidized bed (up to 80% within approximately 20 to 30 minutes). The second stage takes place in a compartmentalized bubbling fluidized bed and leads to the reduction of input material (up to 95%) within 3 to 4 hours, at temperature restricted within the range of 630 °C to 650 °C. Hydrogen used for reduction is mainly produced from cracking natural gas, but alternative, i.e. green sources, can also be used. The elimination of carbon monoxide from reduction gas enables the use of lower operating temperature of the furnace and, consequently, lower particle adhesion and easier control over the reaction. The Circored process enables the obtainment of all types of DRI. Presently, there are no active Circored installations, yet a (currently idle) plant in Trinidad has proven the performance and commercial viability of this process.

2.5. Comparison

Table 2 compares processes described in this chapter in terms of product characteristics, scale of plants and resource consumption.

The most popular technology used for DRI production is the shaft furnace process. Over the last few decades, the MIDREX process has remained the main route for the production of DRI around the world. The second most popular

Table 2. Process comparison

	MIDREX [9, 17, 18]	**Energiron [11]**	**PERED [12, 19]**	**SL/RN [14, 20]**	**Fastmet [16, 21]**	**Circored [10, 22]**
Reactor type	Shaft	Shaft	Shaft	Rotary kiln	Rotary hearth	Fluidized bed
Production capacity, [Mt/y]	0.5–2.5	0.2–2.5	0.3–2.0	≤ 2.0	0.1–0.5	0.5
Metallization degree, [%]	90–94	≥ 93	92–95	88–92	85–92	93–95
Carbon content, [%]	1.0–3.5	1.5–4.5	1.5–3.0	≤ 0.3	3–5	~ 1
Reducing agent	Natural gas, hydrogen	Natural gas, hydrogen	Natural gas, coal (gasified)	Coal	Coal	Natural gas, hydrogen
Power consumption, [kWh/ton] of DRI	~114	0–85	90–120	60–80	80–100	100
Water consumption, [m^3/ton] of DRI	~1.2	0–1.3	0.9–1.3	~1.5	1.8–2.3	0.6

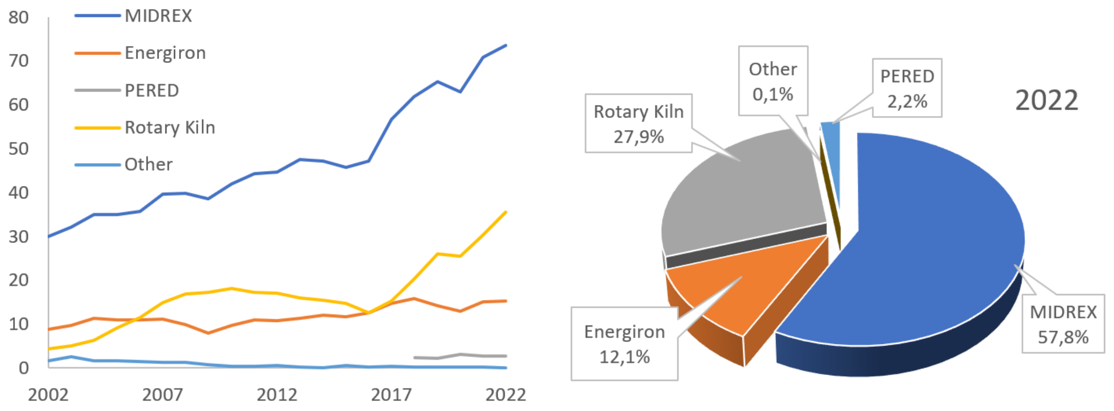

Fig. 5. World DRI production by process, Mt, data from [23]

process is Energiron, yet the last 20 years have not seen its growth as rapid as in cases of other production methods. In the last few years, the PERED process has been gaining popularity, reaching over 2% of the global DRI production in 2022. Production in rotary kilns of various designs has been growing in the last 20 years, especially in India where, alongside bigger plants, hundreds of smaller rotary kilns with a production capacity of between 10 000 and 30 000 tons of DRI have been built [23]. There are also several bigger units producing between 0.06 and 1.5 Mt/y in India and South Africa. Rotary kilns are responsible for over a quarter of global production. Despite the technological maturity of rotary hearth and fluidized bed technologies, they only account for approximately 0.1% of global DRI production. The largest active rotary hearth installation based on the Finmet technology is located in Venezuela and produces approximately 2.2 Mt/y.

3. Europe in comparison with the world

For the last 50 years, the worldwide production of DRI has been steadily and quickly growing, reaching approximately 127.4 Mt (Fig. 6) in 2022 [23]. Most of this production is located in countries having cheap and easily available natural gas. About a third of the entire production of DRI is located in India (43.55 Mt), with Iran occupying the second position (32.9 Mt). The next three largest producers are Russia (7.66 Mt), Saudi Arabia (6.48 Mt) and Mexico (5.84 Mt) [23]. In Europe, the production of DRI has stagnated over the past 20 years and stood at about 0.5 Mt per year, with a drop to 0.15 Mt in 2022 [23]. In view of the foregoing and taking into consideration the fact that even with the use of coal and natural gas, the DRI-EAF is characterised by lower emissions than those of BF-BOF, the European steel industry should focus on replacing blast furnaces and increasing DRI production.

Despite the growing popularity and production capacity of DRI worldwide, in the EU there are only a few operational direct reduction plants. Currently, the biggest DRI installation in the European Union is located in a steel plant in Hamburg, Germany. Owned by ArcelorMittal, the plant consists of a Midrex shaft furnace direct reduction plant, an electric arc furnace, 2 ladle furnaces, a continuous caster and a two-strand wire rod mill [24]. The production capacity stands at 0.4 Mt of CDRI per year and is used for the casting of wire rods for the automotive, construction, infrastructure and mechanical engineering industries. The plant in Germany is the world's oldest MIDREX direct reduction plant still in operation. Another important project is a µDRAL installation in Salzgitter, Germany. It's a demo-scale DRI plant based on the Energiron technology, built by Salzgitter AG in cooperation with Fraunhofer Gesellschaft and Tenova. The plant was launched in 2022 and its operation is based on a flexible mix of hydrogen and natural gas. This installation can produce up to 100 kg of DRI per hour and was also built as a demonstration plant, providing necessary experience and data for future full-scale projects. It is accompanied by two supporting projects, i.e. GrInHy2.0 – a demo-scale electrolytic hydrogen production plant launched in 2021 and WindH$_2$ – a demo-scale windfarm providing green electricity for hydrogen production. Iron produced by the µDRAL plant is used in an integrated steel mill on an on-site basis. The year 2021

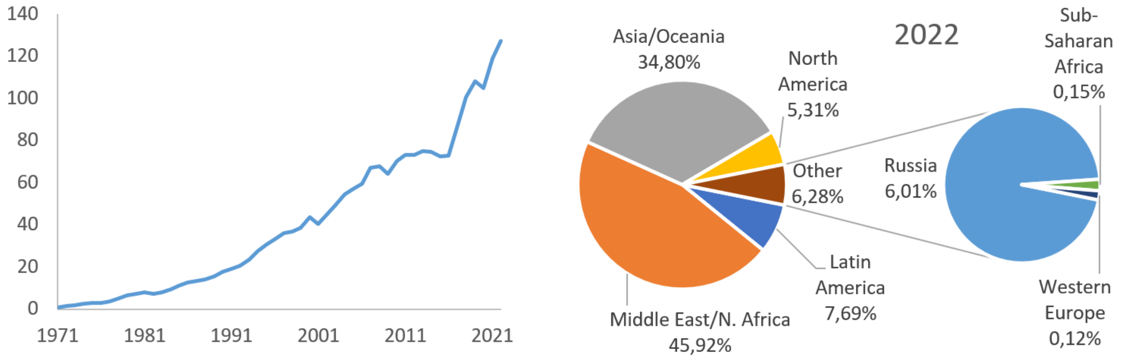

Fig. 6. Worldwide DRI production, Mt, data from [23]

saw the start of DRI production at the HYFOR pilot plant in Donawitz, Austria. The plant is based on a fluidized bed reactor and operated by Primetals Technologies. The process is hydrogen-based.

4. Direct reduction projects in Europe

Following the signing of the Paris Agreement, most of the largest EU's steel producers, including ArcelorMittal, Liberty Steel, LKAB, SSAB, Salzgitter, Tata Steel and Thyssenkrupp have set climate targets regarding the reduction of greenhouse gas emissions. The targets include the partial reduction of emissions by 2030 (within the range of 25% to 50%) and up to 95% reduction or total carbon neutrality by 2050. At least 15 new project including plans for DRI production have been announced in the recent years [25]. HYBRIT is one of the biggest and most advanced hydrogen-DRI projects in Europe. The project aims to produce fossil fuel-free steel on an industrial scale. Its first part, pilot-scale trials in Luleå, Sweden started in 2020 and will continue until 2024. Direct reduced iron is produced in a shaft furnace with hydrogen produced by electrolysis using fossil-free electricity. Another part is a demonstration plant in Gällivare, Sweden, which will be built by LKAB; its target production being up to 1.3 Mt of green DRI per year. Another hydrogen using DRI production pilot-scale plant was announced in August 2023. The facility should be built by HyIron in Lined, Germany. The construction of a new Midrex HBI installation is planned by Metalloinvest in Kursk region, Russia and is predicted to start operation in 2024. A new plant, also based on the MIDREX technology is planned for the Thyssenkrupp Steel location in Duisburg, Germany. In 2021, Tata Steel announced plans for adapting its steelworks for hydrogen use in IJmuiden in the Netherlands. The largest project was announced by an emerging company known as H2 Green Steel. It aims to produce up to 5 Mt/y of green steel by 2030 in Boden, Sweden. The plant plans to use direct reduction with green hydrogen, produced with the help of abundant renewable electricity in the region, and aims to cut CO_2 emissions up to 95 % if compared to traditional steel-making processes. Interestingly, the waste heat from the process will be supplied to a nearby district heating facility. As of January 2024, the project has raised over €4 billion in funding [26]; plans include the start of production as soon as 2025. In terms of Poland, ArcelorMittal has planned the revamping of its plant in Dąbrowa Górnicza and transition to the DRI-EAF route of steel production [27]. The company's target concerning the reduction of CO_2 emission by 2030 has been raised from 30% to 35%, to comply with new a European climate goal known as "Fit for 55" and aiming to reduce EU's emissions by a minimum of 55% by the year 2030. Table 3 contains the summary of the most important projects of DRI production in Europe, planned production capacity and the expected start of operation. In total, the DRI installations announced in Europe until today should be able to produce up to 32.7 Mt/y of sponge iron by 2033.

In order to produce truly green steel by direct reduction, the process has to be provided with hydrogen produced using renewable energy and resources. Most of the current production of hydrogen in Europe is based on grey hydrogen produced with the reforming of fossil fuels. To supply Europe's DRI installations in Europe, several project considering the production of green hydrogen have been announced including H2 Green Steel and Iberdrola projects in Spain [28] as well as 24 projects in Germany. The above-named projects have received 4.6 billion EUR from the European Commission for the development of green hydrogen [29]. Hydrogen obtained from electrolysis is also planned to fuel the DRI installation in Boden. The total production of clean hydrogen announced in Europe by the year 2040 is estimated at 23.8 Mt/y [30]. Plans also include multiple hydrogen storage projects, such as cavern storage alongside the HYBRIT pilot plant in Luleå. Out of 29 already announced large-scale storage projects, 22 are focused on storing pure hydrogen, mostly in salt caverns. However, other technologies, including aquifers, depleted fields and lined rock caverns are also enjoying popularity [30]. Importantly, advancements in electrolysis-based hydrogen production could decrease electricity costs of the DRI-EAF route. Hysata Pty Ltd has developed a new type of capillary electrolyser, raising efficiency to 98% and reducing energy consumption from 47.4 kWh to 40.4 kWh per one kilogram

Table 3. Announced DRI plant projects in Europe [25]

Location	Production capacity, [Mt/y]	Manufacturer/Project	Status o – operational by, c – start of construction
Hamburg, Germany	0.1	ArcelorMittal	o – 2024
Gällivare, Sweden	1.3	HYBRIT	o – 2026
Salzgitter, Germany	1.9	Salzgitter AG	o – 2033
Dunkerque, France	2.0	Liberty Steel	o – not stated
Fos-sur-Mer, France	2.0	GravitHy	c – expected 2024, o – 2027
Kursk region, Russia	2.1	Metalloinvest	o – 2024
Gijón, Spain	2.3	ArcelorMittal	o – 2025
Duisburg, Germany	2.5	Thyssenkrupp Steel	o – 2026
Galati, Romania	2.5	Liberty Steel	o – not stated
Dunkerque, France	2.5	ArcelorMittal	o – 2027
Inkoo, Finland	2.5	Blastr Green Steel	o – 2026
Gent, Belgium	2.5	ArcelorMittal	o – 2030
Bremen, Germany	3.5	ArcelorMittal	o – 2030
Boden, Sweden	5.0	H2 Green Steel	c – in progress, o – 2025

of hydrogen [31]. This technology is being developed on a demonstration scale in Hysata, i.e. a High-Efficiency 'Capillary-fed' Electrolyser Pilot Project in Australia [32].

As of 2022, around 76.7 Mt/y of steel have been produced in the European Union using the BF-BOF route [2]. Assuming that up to 1.2 t of DRI is needed for producing 1 t of crude steel [33] and that all of the above-presented projects will be implemented in their planned forms, it will be possible to replace up to 36% of steel currently produced using BF-BOF. If the entire production is powered by green energy and green hydrogen, it will be possible to eliminate nearly 60 Mt of CO_2 emissions each year. However, even if all these optimistic assumptions come to fruition, green steel projects will still come with a significant price tag. In 2018, it was estimated that operational costs of the DRI-EAF route based on hydrogen reduction were approximately 50% higher than those of the traditional BF-BOF process (624 vs 415 EUR/t of steel respectively) [34]. In the same article it was also estimated that investment costs (CAPEX) for the DRI-EAF route, calculated as annual payments, would equal approximately 105 EUR/t of steel. Accurate approximations concerning DRI installation construction costs are difficult to assess as companies rarely share any precise data related to the projects. Often, investment-related estimates are of only initial nature, without any details as to what is included in budgets of DRI or EAF installations, green energy production facilities (like windmills and solar panels) or hydrogen generation plants. It is rarely known whether announced values constitute entire investment budgets. It should also be noted that large project tend to significantly exceed their originally estimated costs.

The project-related data presented in Table 3 (mainly based on information from press releases and companies websites, compiled by Green Steel Tracker [25]) reveal significantly varied estimates, ranging from approximately 245 million to 1600 million EUR per 1 Mt/y of DRI production. In addition, these estimates should exclude the projects in Bremen, Germany and Boden, Sweden, as the announced investments costs are extremely low in comparison with the remaining projects. For this reason, they are probably not representative of real budgets (e.g. no information was found in relation to the budget of the Liberty Steel project in Dunkerque, France). Mostly, i.e. 7 out of 11 projects under consideration, are kept within the range of 400 million to 850 mil EUR/(Mt/y). The highest cost per Mt/y is connected with the project located in Inkoo, Finland, i.e. a green steel and hydrogen production facility. Only two more projects exceed 1 billion EUR per 1 Mt/y, i.e. the one in Hamburg by ArcelorMittal and the GravitHy in Fos-sur-Mer, yet both keep their budgets below 1.2 billion EUR per 1 Mt/y. As mentioned before, the above-presented numbers probably account for different types, parts and amounts of DRI-EAF installations, therefore comparisons representing any reasonable degree of certainty are problematic. In 2020, in relation to the HYBRIT project it was estimated that the fully commercial 2.5 Mt/y MIDREX-based DRI unit, with an approximate electrolysis capacity of 1000 MW, could cost about 20 billion SEK (i.e. about 1800 million EUR as of the report draw-up date) [35], constituting 720 million EUR per Mt/y of green DRI. In 2021, in the final report of Green Steel for Europe, project investment needs for industrial DRI production plants using 100% hydrogen are estimated at 250 million EUR for 1 Mt/y of crude steel (500 million EUR including EAF) [36]. Assuming that about 92 Mt of DRI should be produced in the EU every year in order to replace the BF-BOF route, in extreme cases between 22.5 billion EUR and 147.2 billion EUR could be needed to build necessary installations. According to more conservative calculations, estimates are restricted within the range of 37 billion EUR to 78 billion EUR. Acquiring such funds as well as delivering multiple big projects on time and under budget pose a significant difficulty and constitute a great challenge in transition to green steel in Europe, particularly if additional and unforeseen problems such as major supply chain disruptions or disturbance triggered by geopolitical events might take place, possibly slowing down or even stopping projects at any stage.

In order to tackle the climate change, the European Commission has started international projects within the Horizon Europe programme. One of such projects is *Maximise H2 Enrichment in Direct Reduction Shaft Furnaces* (MaxH2DR) [37]. Its consortium consists of 10 participants, including academic and industrial partners from 7 European countries. The MaxH2DR project focuses on providing missing knowledge and data concerning direct reduction processes and maximising the use of hydrogen as reductant. The project also aims to provide necessary know-how to scale up hydrogen DRI installations. The achievement of this goal necessitates the performance of experimental tests of properties and conditions of materials and reactors as well as the development of digital toolkits in the form of models. Some part of the experimental work related to this project, concerning the preparation of sinters (industrial and with biomass as fuel), the performance of small-scale direct reduction trials and the identification of material characteristics, is taking place at Łukasiewicz-GIT, where an experimental-scale furnace for direct reduction has been installed. Another project co-implemented by Łukasiewicz-GIT and tasked with supporting the process of transition to green steel is *Upgrading of Low-Quality Iron Ores and Mill Scale with Low Carbon Technologies*" (TransZeroWaste) [38]. Started in December 2022, within the Horizon Europe programme, the project involves collaboration of 12 organisations from 8 countries. The primary goals of the project include the recycling of waste materials such as scale, the upgrading of low-quality iron ores and the development of processes enabling cold pelletization, briquetting and material preparation for direct reduction in the shaft furnace and fluidised bed. The project results will help to provide emerging DR installations and electric furnaces with quality materials and reduce raw iron ore consumption.

5. Summary

As the traditional BF-BOF route of steel production is responsible for the significant part of greenhouse gas emissions in Europe, alternative production methods are enjoying growing popularity. There are several commercially proven processes of DRI production having a lower carbon footprint than that of the BF-BOF route, even where fossil fuels are used as the reducer of iron ore. Shaft furnace processes such as MIDREX, Energiron and PERED as well as rotary kiln installations are the most popular solutions responsible for the production of 99.9 % of DRI worldwide. The shaft furnace and fluidized bed-type DR installations are characterised by a significant advantage in dealing with greenhouse gas emissions as they can be presently used with natural gas and are relatively easily switchable to hydrogen when adequate green H_2 production is available. For decades, the DR-EAF route of steel production in

Europe has not been developed on any meaningful scale. However, the last few years have seen several companies announce great investments in new construction projects of more environmentally friendly direct reduction installations across the continent. Most of these projects are expected to start operation in the second half of the current decade and, if expectations are met, will account for a significant part of European steel production, hopefully replacing some of currently operating blast furnaces. Other projects, of supporting nature, are concerned with the production and storage of green hydrogen. Additional R&D projects, including MaxH2DR and TransZeroWaste, will help to fill the knowledge gap required to ensure complete transition to green steel and achieve carbon neutrality by 2050.

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