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History and Current State of Mining in the Kryvyi Rih Iron Ore Deposit

Mykola Stupnik and Volodymyr Shatokha

Abstract

In 2021 one of the world's largest iron ore deposit in Kryvyi Rih (Ukraine) celebrates 140 years of its exploitation history. During the whole period of its existence the deposit has played and continues to play an important role in the development of Ukraine's economy, being the main basis of its iron and steel industry. More than 6 billion tons of marketable iron ore extracted during this period and some 20 billion tons of waste rock has been mined. The deposit constitutes 82% of Ukraine's iron ore output making the country the 7th biggest producer and 5th biggest iron ore exporter with value of USD 4 billion in 2019. In this chapter the historic aspects of deposit's development and current state of its exploration are analyzed, including processing techniques employed to produce high grade iron ore concentrate, sinter and pellets. Characteristics of iron ores' mineralogical composition and the features of the deposit's geological genesis are also presented. Special attention is paid to the ongoing and planned modernization and deployment of innovative technologies aimed to enhance the competitiveness and to reduce environmental footprint of exploration.

Keywords: iron ore, deposit exploitation, beneficiation, sintering, pelletizing

1. Historic introduction

In 140 years of history, Kryvyi Rih has gone through an impressive path of transformation: from a provincial town in the South of the Russian Empire to the main iron ore base of the Soviet, then – Ukrainian, steel industry, closely involved in the processes of global trade. At present, proven resources of iron ore in Ukraine are estimated at 6.5 billion tons of crude ore (the fifth largest reserve in the world) [1] of which around 70% is deposited in Kryvyi Rih.

The Kryvyi Rih iron ore deposit experienced ups and downs with several distinct periods of formation and development. The settlement of Kryvyi Rih, established as the Cossacks winter-abode in the XVIII century, remained rather unremarkable tiny inhabited area for a long time. The situation changed drastically in the XIX century greatly after the beginning of iron ore industrial mining.

Iron ore deposits were discovered in late 30s of the XIX century. Substantial studies conducted by local entrepreneur Alexander Pol proved the feasibility of the deposit development and in 1880 he initiated the establishing in Paris of the company Societe Anonyme Minerais de Fer de Krivoi Rog with the capital of Franc 30 million owned by French major shareholders (**Figure 1**), which started the iron ore mining in 1881.

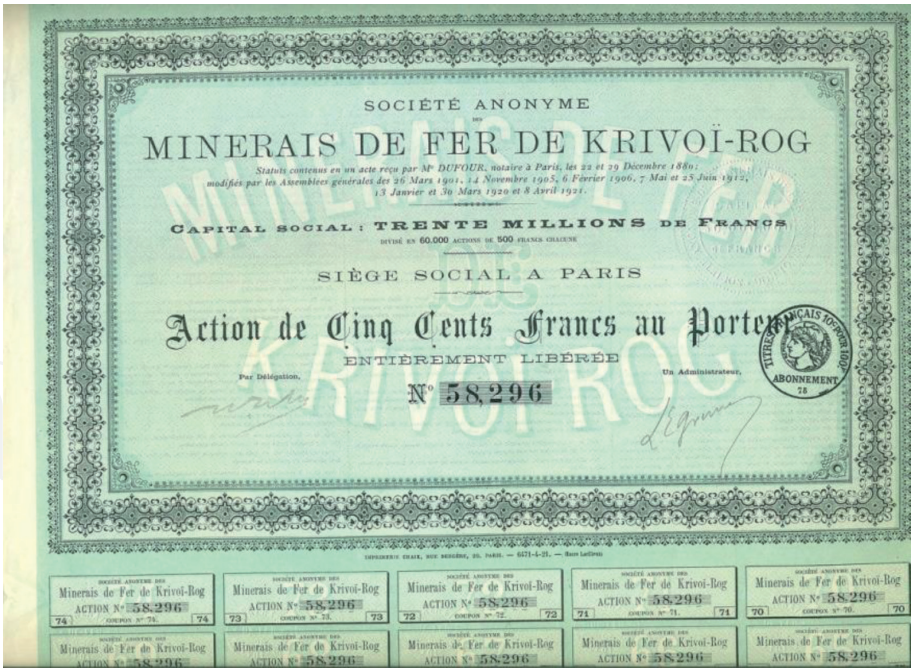


Figure 1.
Share of Societe Anonyme Minerais de Fer de Krivoi rog.

Initially, iron ore mining was made almost completely manually (**Figure 2**). Most part of the mined ore was delivered eastwards over the distance of roughly 400 km by horse and cart (including crossing ca 1 km wide Dnipro river by ferry) to the factories of Novorossiysk Coal, Iron & Rail Production Company. This company was established yet in 1869 (first blast furnace was blown-in in 1871) by a British-Russian consortium initiated in the Donetsk region by John Hughes, a Welsh entrepreneur. Transportation conditions remarkably changed after launching of the railway connecting Kryvyi Rih iron ore deposit with coal deposits of Donbass via the bridge across the river of Dnipro commissioned in 1884, which boosted industrialization over the large, previously rural, area along the railroad.



Figure 2.
Iron ore mining in Kryvyi Rih (1899).

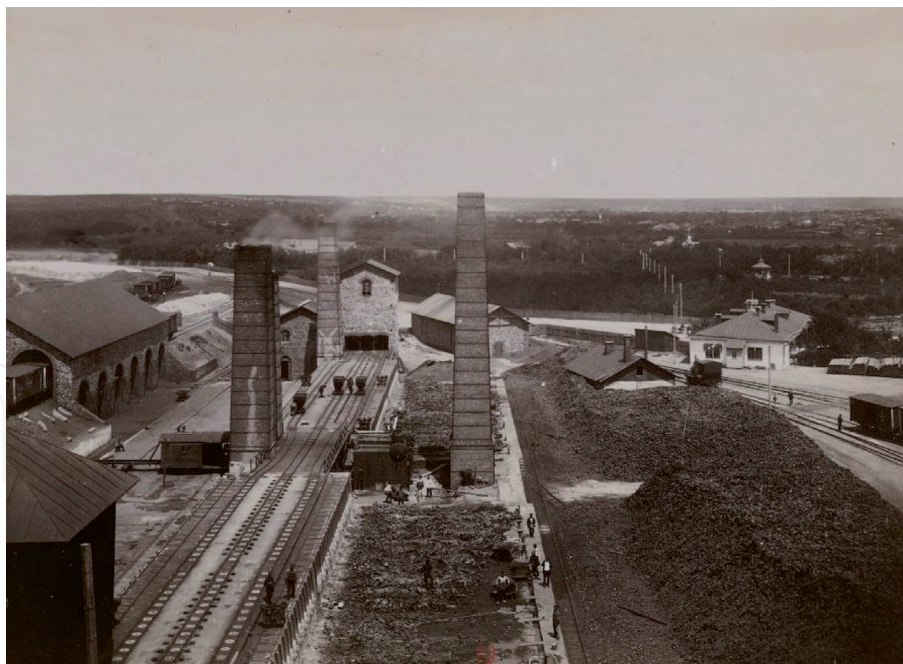


Figure 3.
Gdantsevka ironmaking plant (1899).

In 1885 the mentioned above Novorossiysk Company started also iron ore mining in Kryvyi Rih area, based on British funds. It was followed by starting several other mines, owned mostly by international capital represented with Belgium, Great Britain, France and Switzerland. In addition to manufacturing organization, leading foreign experts have been assigned to deliver mining and metallurgical businesses towards the best European practice. Already by 1887, Kryvyi Rih became the dominant iron ore extraction site of the Russian Empire. In 1892 Gdantsevka Ironmaking Plant (**Figure 3**), also owned by Societe Anonyme Minerais de Fer de Krivoi Rog, was put into operation in the outskirts of Kryvyi Rih. The major part of iron ore extracted in Kryvyi Rih deposit was consumed in Russian Empire, and 10-20% was exported.

In the beginning of the XX century as many as 63 mines have been in operation with cumulative depth of more than 100 km [2]. Each mine was a separate unit with its own infrastructure and administration. The largest production volume of 6.2 Mt. was achieved in 1913, constituting 72% of total production of iron ore in the Russian Empire. Almost 20 thousand employees worked at the mines, 40 engineers controlled the production, 7 of them were foreigners.

However, during World War I followed by the Bolshevik Revolution (1917) and civil war lasted through 1921, the extraction of ore practically ceased: during seven months from January to July 1918 just 264 kt of iron ore was supplied, whereas before the war average monthly supply was around 480 kt. By August 1918 all iron ore mines in Kryvyi Rih were stopped and most of them – flooded [3].

2. Post WWI reconstruction and industrialization

After a kaleidoscopic change of ruling powers, Soviet regime was established in Kryvyi Rih region by the beginning of 1920. Iron ore was essential for reconstruction of industry, so local authorities were subordinated directly to Kharkiv, the first capital of the Ukrainian Soviet Republic. Initially, within the Kryvyi Rih deposit the martial law was imposed, but such measure was not successful and therefore it was decided to return to economic management instruments.

Reconstruction took place in very difficult conditions: famine, ruin, lack of materials, and shortage of workers. Initially, only seven mines were brought into operation. In 1927 as much as 3.5 Mt. of iron ore was mined being just 56% from 1913 level.

Since 1927 the new mining technologies have been introduced replacing the widely used cut and fill stoping method. In 1928 the first “Bucyrus” excavators were supplied from the USA along with 12 scraper winches, 7 conveyers and hammer drills of various manufacturers. The iron ore output in 1930 reached 9.78 Mt., 77% of which was produced by underground mining. Fifteen new mines equipped with an up-to-date machinery were built during the First Five-Year Plan period (1928-1932). Further mechanization of mining operations resulted in drastic increase in labor productivity and by 1940 the annual output reached 19 Mt. [4].

The mining was ceased by August 8th, 1941 - few days before Kryvyi Rih was occupied during World War II. To prevent usage of mines by the invaders, most of the equipment was transported to the mining enterprises of Ural. Units weighting over 100 t were blasted. Most of miners were also evacuated. However, more than 16 Mt. of iron ore was left in stocks.

Reconstruction of mining enterprises during German occupation was sluggish, focused mostly on nearby Nikopol manganese ore deposit being essential for the manufacture of advanced steel grades, whereas Kryvyi Rih with its iron ore stock and a huge amount of equipment turned into scrap was used as auxiliary source of iron charge in steelmaking. Demand for iron ore was hindered by slow reconstruction of coal mines in Donetsk deposit and of steelmaking enterprises on the occupied area, destroyed before the Soviet Army retreat. As a result, iron ore mining did not began until the end of 1942 and extraction of high-grade ore was started only in May 1943.

In June 1942, the removal of ore from the stock began, resulting in usage of 347 kt by the end of the year. In addition to this, from April to September 1943 about 385 kt of ore was mined. As the whole, during the period of occupation 1.78 Mt. of iron ore was taken, out of which 1.4 Mt. from the stocks [5].

In November 1943, anticipating Soviet Army's offensive, the invaders destroyed equipment, transport facilities and workshops of almost all reconstructed enterprises. As the result, out of 77 producing and servicing shafts, 54 shaft mouths were exploded or destroyed completely to the depth from 6 to 15 m. So, within 30 months the mines and the equipment have been destroyed twice.

3. Post WWII reconstruction and further development

Reconstruction of industry with the implementation of large-scale projects has started after the liberation of Kryvyi Rih in February 1944. While the miners began to return from evacuation, the government adopted the law stipulating reconstruction of mines and of mining industry's infrastructure. In just in one year, 32 mines were reconstructed and put back into operation. Another 11 large mines and 15 ventilation units were put into operation in 1946 and annual output reached 6 Mt. The plan of reconstruction and development of Kryvyi Rih mines was drawn up aiming to reconstruct and build 35 large and medium-sized mines with a total annual designed capacity of 26 Mt. This plan was successfully fulfilled and by 1950 ore mining exceeded pre-war level.

Initially, to modernize the facilities and improve performance, mostly inexpensive and simple in implementation measures have been applied; however, since the beginning of 1960s, general reconstruction of mines included application of new

technologies and equipment aimed at advanced level of mining operations. This included deepening of more than 40 mines to the depth from 200 to 1250 m with the cumulative deepening by about 28 km. Mines with inclined shaft were also built during this period.

Construction of Mining and Processing Plants (MPP), large factories comprehensively encompassing production steps from mining through high grade concentrate (some factories also produced pellets or sinter), manifested beginning of new era of mining development in Kryvyi Rih. Supply of high quality agglomerated iron ore materials also greatly contributed to boost development of steelmaking industry.

The first attempts to beneficiate ferruginous quartzite were made in 1930s at the experimental plant, and studies in this direction have been continued after WWII, so research and industrial expertise had been already in place when the decision to build the Southern MPP was adopted in 1952, which produced its first concentrate in 1956. The success of the enterprise with annual mining and beneficiation capacity of 9 Mt. facilitated further construction of similar enterprises and increase in production capacity of existing plants. From 1959 through 1966 another four MPPs - Novokryvorizkyi, Northern, Central and Ingulets - were built on different sites in and around the city of Kryvyi Rih. All plants had almost identical structure including open pit mines for iron ore extraction and beneficiation plants to produce concentrate (**Figure 4**). All MPPs except of Ingulets have been also equipped with plants producing sinter or pellets. Production of iron ore in Kryvyi Rih peaked in 1978 at 120 Mt., when in the aftermath of economic stagnation the demand for iron ore ceased to grow.

Kryvyi Rih was also one of the major suppliers of iron ore materials to the Central-East European Countries members of former Council of Mutual Economic Assistance (CMEA). In 1984 Soviet Union, East Germany, Czechoslovakia, Romania and Hungary initiated the latest large collaborative project of CMEA - construction of new iron ore beneficiation plant near Kryvyi Rih to produce for the countries involved the iron ore concentrate from oxidized quartzites with annual designed capacity of 9.1 Mt. of concentrate. Romania alone invested US\$526 m out of US\$1.6bn totally spent. However, following the collapse of communist regimes, the construction has never been finished [6].



Figure 4.
One of the world largest open pits of Ingulets MPP: Depth 520 m, designed capacity by crude ore - 38 Mt./year.

4. Sector development in modern Ukraine

4.1 General development trends

Collapse of the USSR in 1991 broke established supply chains and stopped large infrastructural projects thus substantially reducing demand for steel. Therefore, the iron ore production in Kryvyi Rih in early 1990s plunged down as shown in **Figure 5**. Mining enterprises faced a severe financial situation. Profit and available capital decreased drastically: up to 80% of transactions in the steel sector were made via barter schemes during this period, impeding accumulation of capital [8].

Further drop of iron ore output was prevented in the frames of a large scale “sectorial experiment” covering the entire mining-metallurgical complex of Ukraine and conducted from August 1999 to January 2003, providing enterprises with state assistance and allowing companies to accumulate finances for improving technologies and environmental safety under special taxation regime [8]. The state of Ukraine’s mining sector was improved and iron ore output started to rapidly grow, as shown in **Figure 5**. Meanwhile export opportunities have been gradually exploited, especially after 2008, when the domestic demand shrank drastically in the aftermath of financial crisis followed by recession. **Figure 6** compares iron amount of the produced ore with the output of pig iron (blast furnace ironmaking is the sole large consumer of iron ore products - sinter and pellets in Ukraine). The both values, after being fluctuating almost in parallel, since 2009 gradually decouple from each other, and in 2019, first ever, output of pig iron drops by 2.4% although the iron amount of the produced ore grew by 2.8%. This illustrates orientation of mining sector rather not on the domestic needs but on the global markets - as shown in **Figure 7**, since 2015 over 60% of the iron ore output is exported.

4.2 Current characteristics of deposit

In Ukraine, by the exploration stages, reserves are coded differently from International system applied by CRIRSCO (Committee for Mineral Reserves International Reporting Standards) and the **Table 1** for conversion is shown below. Collectively, the sum of A + B + C1 categories is referred to as a proven reserve.

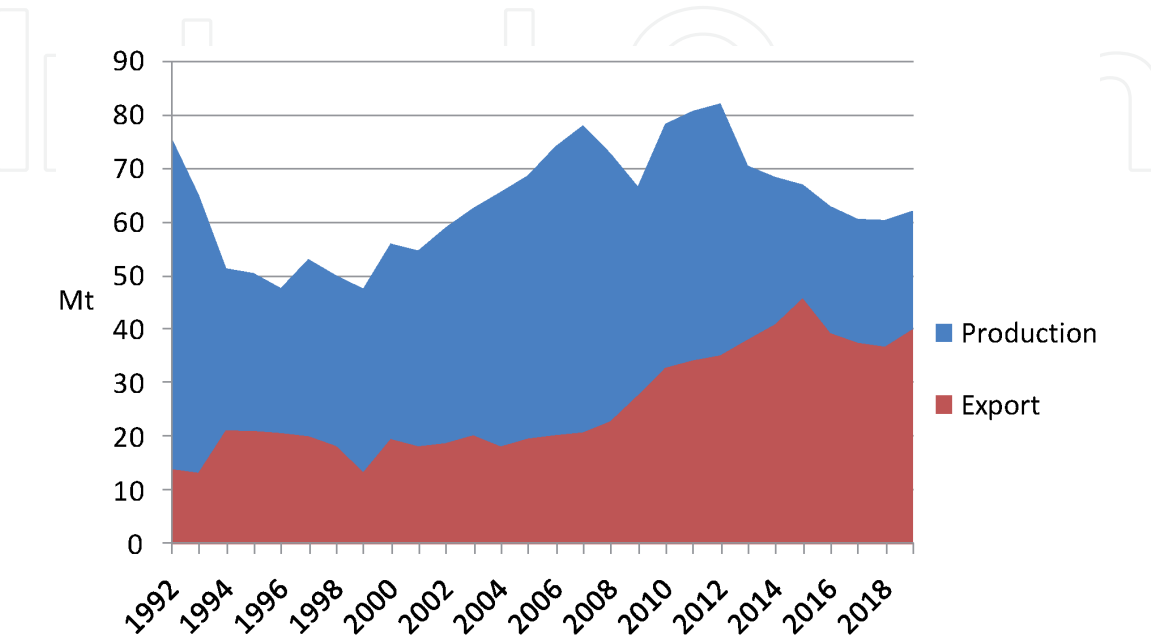


Figure 5.
Production and export of usable ore (elaborated by authors on [7]).

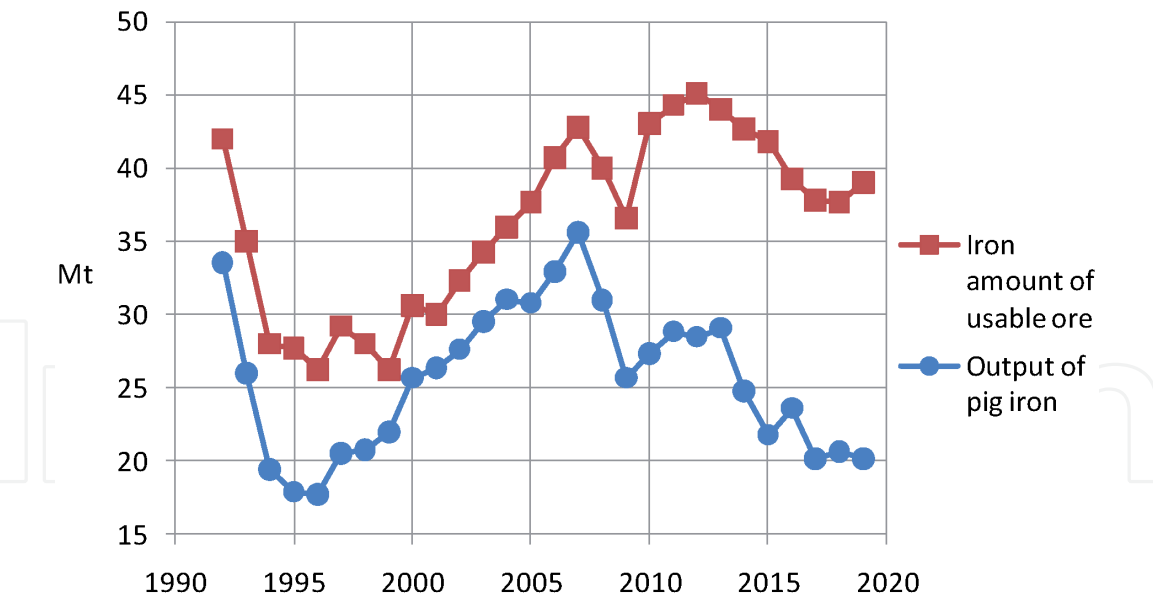


Figure 6.
Iron amount of the produced ore versus output of pig iron in Ukraine (elaborated by authors on [7, 9]).

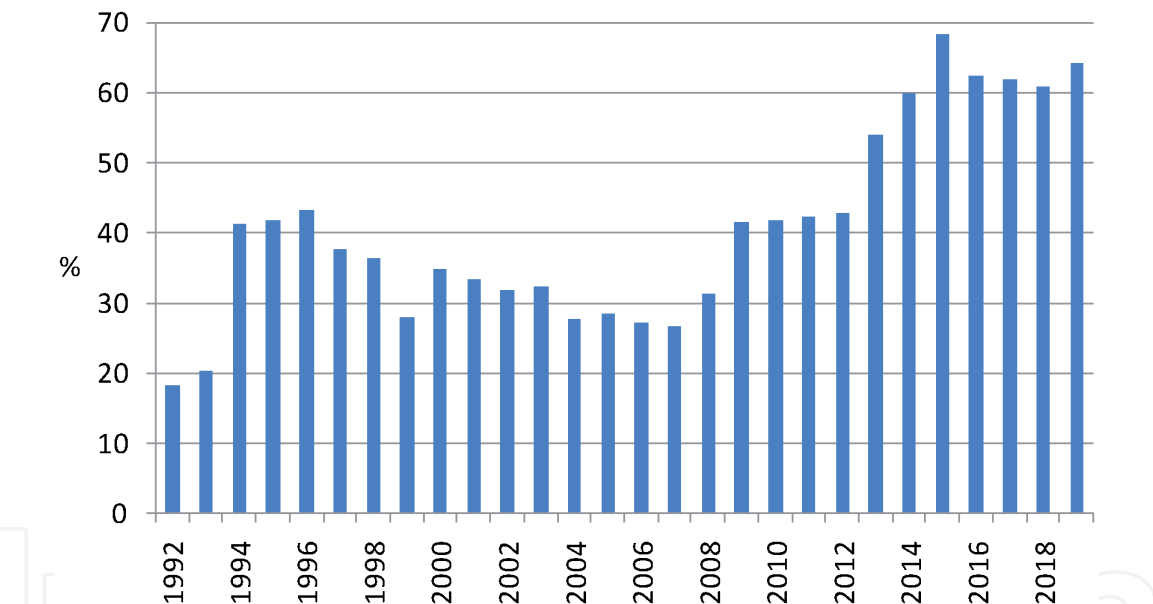


Figure 7.
Share of export in the usable iron ore production.

CRIRSCO	Classification	Measured		Indicated	Inferred
	Level of confidence	High		Reasonable	Low
Former Soviet code	Classification	A - fully explored	B - studied based on industrial development	C1 - studied based on the results of pilot development and testing	C2 - studied based on the results of testing and exploration
	Level of confidence	Proven			Probable

Table 1.
Table of correspondence between CRIRSCO and former soviet codes.

Over 70% of Ukraine’s proven reserve is located in Kryvyi Rih iron ore deposit. Iron ores mainly belong to the following three geo-industrial types: rich magnetite–hematite-martite ores, ferruginous quartzites and brown ironstones. Rich ores are used without concentration. Magnetite and cummingtonite-magnetite quartzites and brown ironstones of Kryvyi Rih deposit are concentrated by relatively simple methods – washing and magnetic separation. Oxidized quartzites and brown ironstones require roasting-magnetic and gravity-floatation methods of concentration.

Rich ores occur in bodies of 10-60 m and, occasionally, up to 100 m thickness. The iron content varies from 46% to 70%, phosphorus and sulfur contents – from 0.01% to 0.03%.

Magnetite and oxidized ferruginous quartzites are encountered in bodies of up to 100-200 m and, occasionally, up to 500 m thickness. The iron content in such ores varies from 14% to 46%, phosphorus content - from 0.03% to 0.16% and sulfur content - from 0.02% to 0.24%.

Currently, approximately 51% of all proven reserve is exploited. Substantial part of the reserve is not considered for mining in the near future for economic reasons. Along with underground enterprises, five large enterprises mine the ore in 10 open pits at depths of 150-450 m with further processing. Since the early 1970s the open pit mining method became and to date remains predominant as shown in **Figure 8**. In terms of maintaining production on current level, available reserves of iron ores covered by ongoing open pit mining activities remain sufficient to ensure functioning of mining and processing plants in the long term perspective as shown in **Table 2**.

Currently, rich iron ores and magnetite quartzites are mined via the underground method by Kryvyi Rih Iron Ore Plant, ArcelorMittal Kryvyi Rih and Sukha Balka. Magnetite and oxidized quartzites are mined using the open pit method by Ingulets MPP, Southern MPP, Northern MPP and Arcelor Mittal Kryvyi Rih, whereas Central MPP applies both underground and open pit mining methods.

The depth of occurrence of commercial reserves of iron ore in Kryvyi Rih reaches 2.7 km, therefore underground mining remains essential. However, mining conditions are rather complicated - eight underground iron ore mines are functioning with mining operations conducted at depths of 600-1300 m in particularly risky underground conditions. Three of underground mines are operating in a flooding prevention mode.

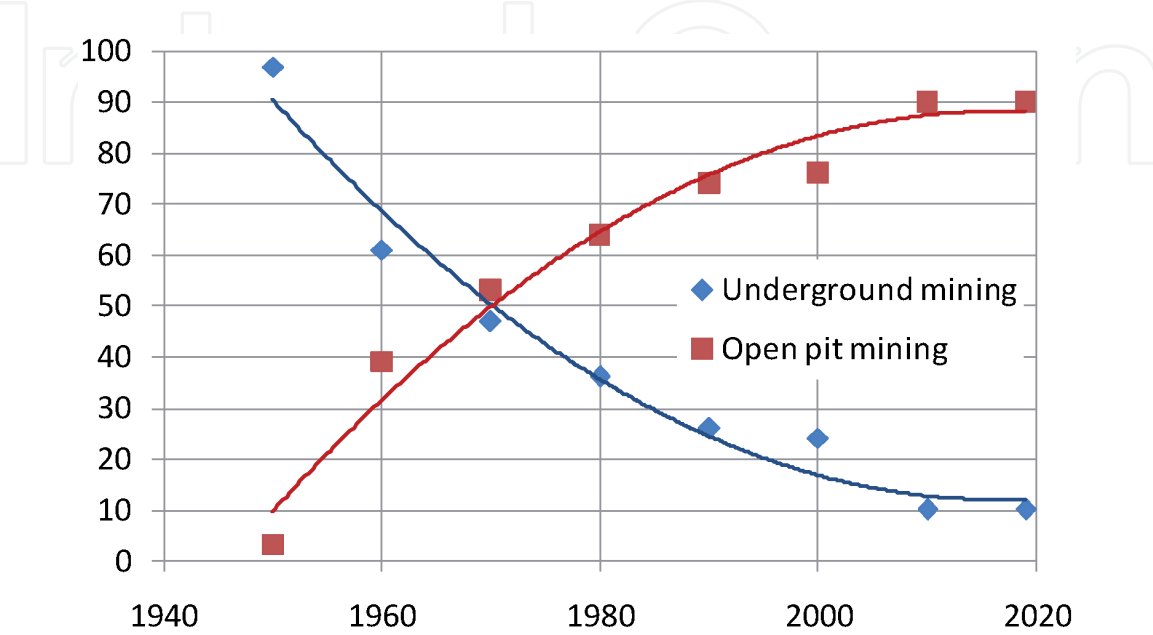


Figure 8.
The ratio between an underground and an open pit iron ore mining in Kryvyi Rih (%).

Reserves	ArcelorMittal Kryvyi Rih		Northern MPP		Ingulets MPP	Central MPP			Southern MPP
	# 2-bis	# 3	Pervomaiskyi	Annivskyi		# 1	# 2	# 3	
Proven reserve	265.619	1126.037	858.345	870.873	1956.064	197.078	209.902	157.202	1045.040
Available within current mining boundaries	236.625	750.084	501.458	372.819	972.060	15.912	214.463	152.472	1045.040
Resource endowment, Years	29	27	28	50	33	39	34	157	35.7
Accessed reserve	29.593	30.503	5.74	1.42	4.42	3.24	2.4	0.9	22.8
Developed reserve	5.795	11.577	3.15	0.51	0.52	1.57	1.5	0.5	0.9
Blocked out reserve	1.556	2.792	0.13	0.16	0.15	0.926	0.77	0.16	0.2

Table 2.
Iron ore reserves covered by ongoing open pit mining activities in Kryvyi Rih, Mt. [10].

Generally, the analysis of the situation of underground mining in Kryvyi Rih reveals a threat of gradual reduction of the resource provision and consequent decline of the commercial potential. Iron ores in the amounts of the billions of tons are accounted at underground mining enterprises as so called balance iron ore reserve (meaning the resource which mining is economically feasible and which parameters satisfy accounting requirements). This resource can provide the basis for mining development for more than 100 years ahead. However, in fact, the situation is far from optimistic for individual enterprises and for the deposit as a whole. Currently, underground mining of naturally rich iron ores is carried out only at seven mines of three mining enterprises and one more underground mine exploits magnetite quartzites.

Overall, during the last 10-15 years, the gap between the designed capacity and actual production of enterprises was reduced due to pressure from the market that forces the enterprises to adapt design solutions of current and new projects in order to minimize expenditures, increase technological efficiency and enhance competitiveness. However the drawbacks are not yet overcome and technology still lags behind the market demands, so capacity utilization of most mines does not exceed 70-80%. Such capacity utilization weakens competitiveness on the global market and undermines Kryvyi Rih deposit's production potential.

In 1990, the share of rich ore in the total iron ore production in Kryvyi Rih was 26.3%, while in 1995 it was reduced to 23.5%, and at the end of 2019 – to 14%. Currently, compared to 2007 (the most successful year in the period from 1995 to 2019), the production volume decreased from 62.98 Mt. to 58.27 Mt. or by 7.5%. A more significant drop is observed in comparison to 1990, making 59%.

Key reasons for production decline of rich iron ores in Kryvyi Rih can be summarized as follows:

1. Continuous and intensive exploitation of deposit as a whole, delineation of individual deposits to greater depths, decommissioning of unprofitable mines, and depletion of reserves result in lower resource endowment of existing mines.
2. Lack of efficient technologies for processing of extracted raw ore result in relatively low iron content of ore (55-57%), high losses (up to 12-15%) and ore dilution (up to 10%) in mining.
3. High rate of mining operations deepening (13-16 m per year) is coupled with limited technical capacity of hoisting installations as well as with general deterioration of mining and geological conditions at deeper horizons are followed by a decrease in the mines' productivity.
4. Financial aspects include constant growth in maintenance costs of existing facilities due to reduced levels of mining, increased mining capital and high development cost at new deeper horizons. Increased cost of fuel, energy and of processing equipment only exacerbate the current situation.
5. Some market-related problems shall be noted such as insufficient competitiveness of marketable products compared with the major global producers, low domestic demand and increasing volumes of sinter grade ore imports.
6. Investments to R&D are continuously insufficient thus impeding delivery of innovative technologies capable for addressing current industrial needs.

The problems listed above are accompanied by the lack of scientifically sound strategy for underground mining on the national level. Due to long term and

intensive exploitation of underground mines in Kryvyi Rih, the reserves of naturally rich iron ore significantly decreased and make 309.2 Mt. at the depth above 1500 m. The depth of mining has reached 1200-1400 m and approaches the critical lifting capacity of mines. The average reserve endowment makes 22.4 years, which, at first glance, is sufficient for economically sustainable development of underground mining enterprises. However, taking into account the duration of all the operations required for commissioning of new deeper horizons as well as subsequent involvement of new iron ore material types or transition to a combined two-step mining and hoisting scheme, the development perspective is rather uncertain.

When evaluating the state of the raw material base, we cannot omit the fact that exclusion of low-grade lump ores from the total unprocessed ore supply in order to achieve required quality of marketable products results in even more intense exhaustion of the reserves. The yield of marketable products at different mining enterprises varies in the range from 84% to 86%. But even with this yield, the iron content of marketable iron ore products usually reaches just 57.5-59.0%, which is not sufficient for competitiveness. Noteworthy, in the longer perspective the discharge of substandard raw materials is not only inevitable, but can even increase.

Considering the current state of the deposit, we anticipate that, in the next 5-10 years, the enterprises can face a number of difficulties in maintaining optimal production capacity and, in 15-20 years, a greater reduction in output and closure of some mines. This process is irreversible from technical and economic points of view, and will have sensitive social consequences in the region.

At the same time, as much as 589.7 Mt. of rich iron ore is deposited at depth from 1500 to 2500 m. In addition, 4.2 Gt of easily concentrated magnetite quartzites locates at depth of 30-1500 m (2.2 Gt at operating mines and 2 Gt at temporarily closed mines). Most of magnetite quartzites occur at depth of up to 700 m.

4.3 Environmental aspects

Analysis of the environmental issues of iron ore mining requires separate study and goes beyond the scope of current chapter. Therefore we address this topic here very briefly.

Currently operating mining enterprises of Kryvyi Rih, including those operating in the flooding prevention mode, pump up to 40 Mm³ of ground water from mines and pits annually, of which highly mineralized water makes 16-17 Mm³ annually. Nearly 30 Mm³ of return water is in a continuous technological loop at the 5 MPPs. Tailing ponds (6 operating and 2 closed ones) of the mining enterprises occupy the area of 5 000 ha and contain over 2 billion m³ of ore concentration wastes. Dumps contain over 13.0 billion t of overburden rocks. Underground voids reach volume of 50 Mm³. Overall, in Kryvyi Rih iron ore deposit on the area of 300 km², a great number of potentially hazardous objects such as underground mines, open pits, tailing ponds, industrial sites, disturbed land and underground voids are located.

4.4 Iron ore quality

The global output of iron ore is in compliance with dynamics of the world economy, yet, in general, development of iron ore mining is quite steady. Total production of crude iron ore has exceeded 3 billion t per year and has tripled since 1999. As anticipated by Fitch in Global Iron Ore Mining Outlook, global crude iron ore production will grow modestly from 3.348 billion t in 2019 to 3.482 billion t in 2028, which represents average annual growth of 0.2% during this period being a significant slowdown from an average growth of 4.5% during 2009-2018 [11]. Therefore, taking into account growing iron ore mining capacities, especially in Brazil, iron ore market shall become

even more competitive. In terms of international competitiveness, the position of Ukraine amongst the other major global suppliers is rather uncertain. For instance, iron content in sinter grade ore supplied from Brazil is 66-67%, from Australia – 61-62%, from Sweden – 67% with silica content in the range of 0.5-3.5%, whereas iron content in Ukraine’s sinter grade ore makes 56-61% with silica content of 18-21.5% [1].

At present, Kryvyi Rih underground mines enhance quality of marketable ore through increasing iron content in the last portion of ore drawn from blocks to 50-52% instead of previously standard 46% as well as through screening out the lean lumps with iron content of 43-48% at the crushing-grading factory. Although this assisted to a general trend of increasing the iron content in the concentrate (evolution of average value for Ukraine is shown in **Figure 9**), application of such methods increases also ore losses in situ and iron losses during concentration and, finally, negatively impacts the enterprise’s economy. At the same time, quality of ferruginous quartzites mined at open pits in terms of iron content and content of impurities was not improved. Generally, the quality of marketable iron ore product remains well behind the advanced foreign practices, despite certain improvements achieved at some enterprises [12].

4.5 Insights for the development strategy

In the current situation, the identification of the priority directions for the further development of the Kryvyi Rih iron ore deposit with the involvement of R&D institutions within the framework of the national and regional economic development strategy is on demand. A broad assessment of the actual condition of the raw material base and, first of all, rich iron ore reserves at depth above 1500 m, allows to foresee four possible options for further long-term development of underground mining:

- 1. Mining of rich iron ores to the depth of the engineering capacities of the existing hoisting facilities (1500-1600 m) with subsequent closure or conservation of the mines.
- 2. Mining of rich iron ores below 1500 m with the use of two-stage ore body opening-up schemes or by radical reconstruction of hoisting complexes’ infrastructure in order to enable the ore hoisting from deep horizons to the surface.

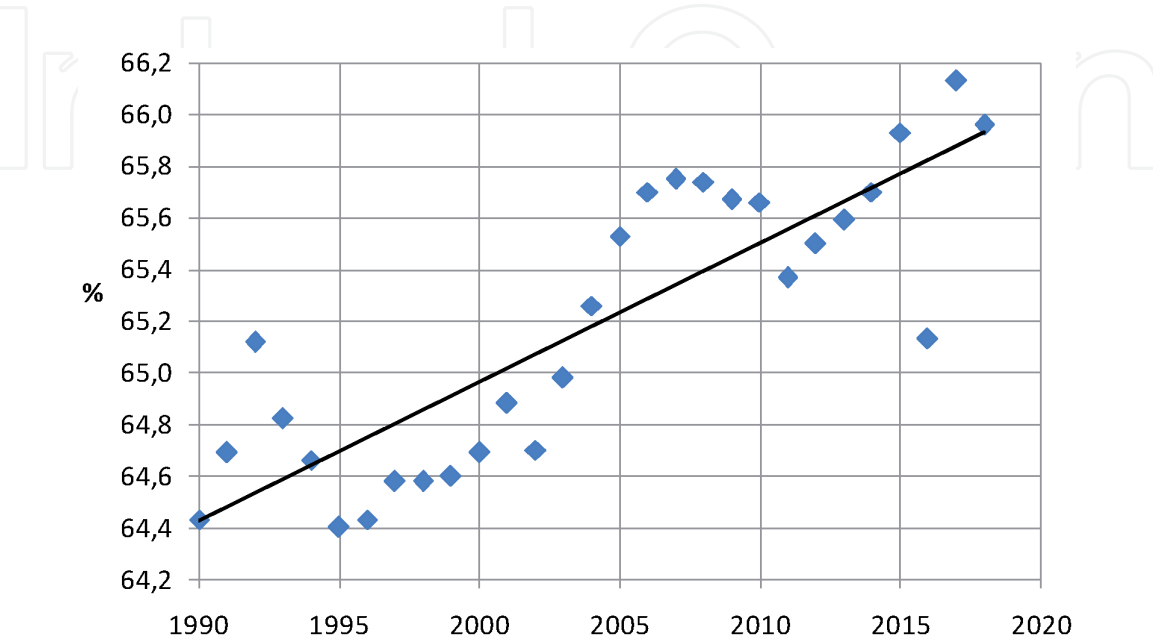


Figure 9.
Average Fe content in iron ore concentrate produced in Ukraine, %.

3. Continuation of rich iron ores' mining above the 1500 m depth followed with the gradual involvement of magnetite quartzites in the areas of operating and temporarily suspended mines and further increasing of the mines' production capacity.
4. Simultaneous mining of rich ores and magnetite quartzites in the fields of operating and temporarily suspended mines.

Since the average supply of rich minerals of underground mining enterprises is only about 22 years, the Option 1 leaves no long-term prospects for the development. For some major mines, for example, Ternovskaya (18 years) and Rodina (17 years), the choice becomes critical. The social consequences of the complete decommissioning of the underground mines throughout the industrial region of Kryvyi Rih will be also very challenging. Moreover, the adjacent territories are likely to be inundated with mining water and water inflows in some pits will also increase. The wet and, in particular, dry conservation of mines requires significant costs for their maintenance. For example, Gigant-Glubokaya and Pervomayskaya mines (both state owned) are currently at the stage of dry conservation and provide flooding prevention for existing mines, pits and adjacent areas. In the case of wet conservation, an irreversible loss of part of the ore reserves, siltation of excavated sites and worsening of the flooding hazard at mining sites and surrounding areas are highly possible.

Options 2, 3 and 4, despite essential difference in the approaches, ensure a certain long term development perspective for mining operations. The advantages are as follows:

1. Retaining of the production and export potential of underground mines and their raw material base is ensured.
2. More holistic approach to development of the iron ore deposits can be applied.
3. Production of high-quality iron ore raw materials through the development of easy-to-process magnetite quartzites present in operating minefields can be increased. The beneficiation of these quartzites using traditional wet magnetic separation technology allows the production of high grade concentrates with iron content of 69-70%.
4. Increasing of production capacity and reducing the hoisting height to the surface may cut the cost of mining in some cases.

However, the choice of the strategy for underground mining shall be based on thorough modeling of the development scenarios for each mining enterprise and for the deposit as the whole. Moreover, the directions of the Kryvyi Rih iron ore deposit development should be seen in the context of both underground and open pit mining, coupled with development of the processing plants. The extraction of magnetite quartzites by the underground method is feasible only in case if the beneficiation facilities sufficient to process the mined ore and to ensure desirable iron content in the concentrate are available. Further deepening of iron ore pits leads to an increase in the haulage distance of rock mass and waste, and, therefore, in the cost of salable products. The gigantic amounts of mined ore and rocks require the additional land allocation for the construction of tailings storage facilities – mostly on highly productive agricultural soils. All of these aspects shall be also taken into account in developing of a strategy for the deposit exploitation.

5. Conclusions

1. Kryvyi Rih iron ore deposit played tremendous role in industrialization of Russian Empire and Soviet Union, and continues to be indispensable part of modern Ukraine's industrial development and the wealth creation.
2. Currently, approximately 51% of all proven reserve is exploited, whereas substantial part of the reserve is not considered for mining in the near future for economic reasons. Since the early 1970s, the open pit mining became and to date remains predominant. Available reserves of iron ores covered by ongoing open pit mining activities are sufficient to ensure functioning of mining and processing plants in the long term perspective.
3. Due to long term and intensive exploitation of underground mines, the reserves of naturally rich ore significantly decreased and make 309.2 Mt. at the depth above 1500 m. The depth of mining has reached 1200-1400 m and approaches the critical lifting capacity. The average reserve endowment of 22.4 years may seem sufficient for further development; however, taking into account the duration of operations required to involve new deeper horizons as well as subsequent involvement of new iron ore types and transition to a combined two-step mining and hoisting scheme, the development perspective is rather uncertain. Scientifically sound strategy for underground mining is lacking.
4. Generally, the quality of marketable iron ore product remains behind the advanced foreign standards, despite certain improvements achieved at some enterprises; therefore, international competitiveness of Ukraine amongst the other major global iron ore suppliers is rather uncertain.
5. The directions of the Kryvyi Rih iron ore deposit development should be seen in the context of both underground and open pit mining, coupled with development of the processing plants.

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