Perm Journal of Petroleum and Mining Engineering. 2022. Vol.22, no.2. P.93-100. DOI: 10.15593/2712-8008/2022.2.6

ISSN 2712-8008
Volume / Том 22 №2 2022
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622+504.7
Article / Статья

Fuel oil replacement – decarbonizing the mining industry (as discussion)

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Замена нефтяного топлива – декарбонизация горнодобывающей промышленности (в качестве обсуждения)

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Received / Получена: 25.02.2022. Accepted / Принята: 31.05.2022. Published / Опубликована: 21.12.2022

Keywords:
hydrogen, mining, decarbonization, diesel fuel, mining dump truck, exhaust gases, fuel cells, ecology.

With the beginning of the civilization development, people began to extract minerals from the bowels of the Earth and transport the rock mass. The main expense in mining operations is the energy required to extract and transport ores, provided by electricity or diesel fuel, which is the main source of energy for mining companies operating in remote areas. Significant disadvantages of diesel equipment are the release of toxic substances, gas contamination of the atmosphere and increased smoke, especially at deep horizons. As a way to reduce carbon emissions and negative impact on the environment, it is important to use alternative fuels, the most environmentally friendly of which is hydrogen. Hydrogen-powered mining equipment does not pollute the air with exhaust gases, which makes the working atmosphere cleaner, especially in deep quarry or underground mining. It should also be taken into account that while the cost of diesel fuel is constantly increasing, the cost of hydrogen fuel is decreasing every year. Diesel and electricity costs in mining operations are often prohibitive given their relative isolation. The operating conditions of mining trucks and other mining equipment ensure the demand for hydrogen energy in the mining industry in terms of its decarbonization.

Ключевые слова:
водород, горные работы, декарбонизация, дизельное топливо, карьерный самосвал, отработавшие газы, топливные элементы, экология.

С началом развития цивилизации люди стали добывать минералы из недр Земли и транспортировать горную массу. Основной статьей расхода при горных работах являются энергозатраты, необходимые для добычи и транспортировки руд, обеспечиваемые за счет электроэнергии или дизельного топлива, которое для горнодобывающих компаний, работающих в отдаленных районах, является основным источником энергии. Существенными недостатками дизельного оборудования являются выделение токсичных веществ, загазованность атмосферы и повышенная дымность, особенно на глубоких горизонтах. В качестве способов уменьшения выбросов углерода и негативного влияния на окружающую среду актуально использование альтернативных топлив, наиболее экологичным из которых является водород. Горное оборудование, работающее на водороде, не загрязняет воздух отработавшими газами, что делает рабочую атмосферу более чистой, особенно в глубоком карьере или при подземном способе добычи. Следует также учитывать, что в то время как стоимость дизельного топлива постоянно возрастает, стоимость водородного топлива с каждым годом понижается. Затраты на дизельное топливо и электроэнергию на горнодобывающих предприятиях часто чрезмерны, учитывая их относительную изолированность. Условия эксплуатации карьерных самосвалов и другого горного оборудования обеспечивают востребованность водородной энергетики в горнодобывающей промышленности в плане ее декарбонизации.

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Please cite this article in English as:
Khazin M.L., Apakashev R.A. Fuel oil replacement – decarbonizing the mining industry (as discussion). *Perm Journal of Petroleum and Mining Engineering*, 2022, vol.22, no.2, pp.93-100. DOI: 10.15593/2712-8008/2022.2.6

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Хазин М.Л., Апакашев Р.А. Замена нефтяного топлива – декарбонизация горнодобывающей промышленности (в качестве обсуждения) // Недропользование. – 2022. – Т.22, №2. – С.93–100. DOI: 10.15593/2712-8008/2022.2.6

Introduction

Global decarbonization largely depends on the eco-friendliness of mineral and raw material extraction technologies. The mineral extraction is a global industry that impacts the lithosphere, atmosphere, hydrosphere, and biosphere, and it is one of the most energy-intensive industrial operations. The energy demands are often covered by electricity or diesel fuel. As the mining industry depends on fossil fuels, it contributes substantially to global warming, being a major source of carbon emissions. Therefore, mining companies face increasing pressure from the society to reduce greenhouse gas emissions. According to the Carbon Disclosure Project report, half of the world's industrial greenhouse gas emissions in 2015 were associated with just 50 companies operating in the fossil fuel extraction and processing sector, including 20 mining companies.

The mining industry development with the widespread use of diesel equipment worsens the sanitary and hygienic conditions in the workplace and the environment, as diesel exhaust gases contain heavy metals and other toxic substances [1–3]. Furthermore, the air saturated with exhaust gases, entering a running engine, does not ensure complete fuel combustion, which leads to increased fuel consumption and, consequently, increased exhaust gases volume. The harmful gases and smoke in the working environment, especially at deeper levels, significantly reduces work productivity due to increased breaks and additional costs for ventilating quarries and underground workings [4, 5], as well as causing personnel health problems and reduced visibility on roads [6–8]. Constant exposure of exhaust gases affects humans, leading to cerebral vascular damage, the nervous system deseases, and other organs damages [9, 10], development of immunodeficiency, bronchitis, and cancer [11, 12].

To reduce staff and equipment downtime, various methods were used, such as artificial ventilation of quarries, water spraying, etc. [4, 5, 13]. However, none of these solutions have effectively solved the problem, and the ecological situation in the quarry worsens. In the close space entry, ventilation conditions become even more complicated, forcing companies to make significant investments into ventilation systems. According to studies [5, 16, 17], ventilation accounts for 30-40 % of the total energy operating costs.

The mining industry decarbonization can lead to significant results, as diesel mining trucks alone account for 30–50 % of total energy consumption at mining enterprises. Currently, there are approximately 28,000 mine trucks operating worldwide, with diesel engines producing 68 million tons of CO_2 annually. This amount corresponds to the total greenhouse gas emissions of countries such as New Zealand or Finland [18].

The depletion of ores with higher content and easier accessibility forces mining companies to look for resources that are located in more remote and deeper areas. As a result, the volume of exhaust emissions increases as mining companies transport mined rock over longer distances in opencast working or extract ore at deeper levels in underground. Furthermore, the applied environmental protection measures are not able to keep up with the rapid extraction and processing growth [12, 19–22].

The decrease in ore content also leads to increase in extraction, loading, transportation, and processing, as well as in energy demand for mining operations. For example, when the copper ore grade decreases from 0.4 % to 0.2 %, it requires seven times more energy [23].

The mining industry decarbonization is crucial for achieving global zero-emission targets by 2050, in order to reduce costs and meet decarbonization goals. It is influenced by increasing social pressure, changes in international and

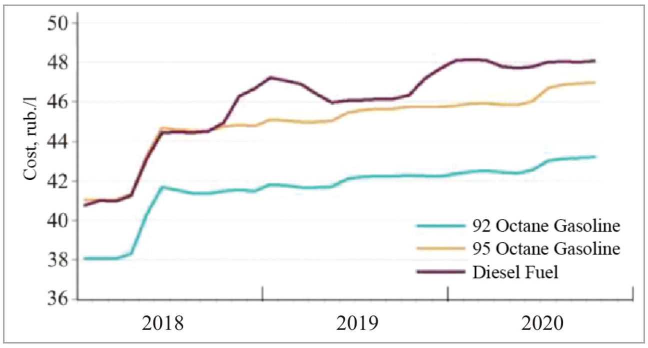

Fig. 1. Retail prices for gasoline and diesel fuel in Russia (rub./l) [29]

national energy standards [24], as well as the opportunity of introducing modern “green” technologies.

In addition, the long-standing environmental issues of mining production are worsened by the constant rise in diesel fuel prices (Fig. 1). As a result, mining companies are considering possible options to reduce greenhouse gas emissions from vehicles as a first step by replacing diesel fuel used for transporting mined rock in the coming decades.

One of the options for expanding the energy resources and reducing environmental impact is the use of alternative fuels obtained from non-petroleum raw materials [1, 25–28]:

- liquefied and compressed natural gas (LNG and CNG);
- liquefied hydrocarbon gases (LHCG);
- synthetic fuels from natural gas or coal;
- ethanol;
- methanol, dimethyl ether (DME), synthetic liquid hydrocarbons (SLH);
- hydrogen.

The main advantage of these fuel types is the lower content of toxic components in the exhaust gases of diesel or gasoline engines (see table). According to data from DNV GL, the least greenhouse gases amount is released when using LNG specifically carbon dioxide, ozone, water vapor, and methane. However, methane has a greenhouse effect that is 20 times stronger than that of carbon dioxide. Therefore, among these fuels, hydrogen is considered the most environmentally friendly, as its combustion produces only water vapor and minimal amounts of nitrogen oxides (NOx).

Hydrogen was first used as a motor fuel for internal combustion engines by the French inventor François Isaac de Rivaz in 1806. Its main advantage was the energy mass density of hydrogen, which significantly exceeds that of diesel, gasoline, and methane. However, in terms of volumetric energy density, even liquid hydrogen falls short compared to diesel and gasoline by a factor of 3.5 to 4.0. Additionally, the challenges related to hydrogen storage and safety have proven to be quite complex. For these reasons, starting from 1870, gasoline was used for internal combustion engines, followed by diesel fuel, and hydrogen fuel was neglected for many years. Currently, the strategic prospects for the use of hydrogen fuel are primarily associated with the potential to reduce greenhouse gas emissions.

The advantages of hydrogen as a motor fuel are the following:

1) practically zero emissions of harmful substances;
2) quiet operation;
3) higher calorific value, 2–3 times greater than the amount of energy obtained from a comparable mass of gasoline;
4) high power reserve and torque;
5) comfortable working conditions for the driver (minimal vibration and no diesel smell);
6) high efficiency coefficient;
7) no need for engine cooling.

Emissions of harmful substances during combustion of various fuel types, g/km, according to [21, 30–34]

Fuel types	CO	CH	NOx	CO_2	Sulfur dioxide (SO_2)	Benz-a-pyrene
Petrol	25–0.15	8.5–0.07	9.1–0.1	203.1	0,009-0.002	0.03-0.003
Diesel fuel	0.1–1.6	0.02–0.2	0.7–1.8	180.5	0.0037	-
Liquefied petroleum gas	19	4.8	8.7	-	-	-
Liquefied natural gas	0.09–0.18	0.055	0.022	189.3	0.0018	
Compressed natural gas	8.5–1.5	4.5–0.2	8.5–0.5	-	-	0.0009–0.0003
Gasoline mixed with hydrogen	3	2.8	4.6	-	-	-
Methanol	28	4.6	4.4	-	-	-
Methanol mixed with petrol	32	5.4	7.6	-	-	-
Hydrogen	0	0	2.5	-	-	-

The disadvantages of hydrogen as a motor fuel are:

1) high volatility, which has the risk of hydrogen filling a confined space within the driver's cabin;

2) fire and explosion hazards when interacting with a heated exhaust manifold and motor oils;

3) lack of developed infrastructure (a limited number of filling stations);

4) hydrogen storage requires larger fuel tanks than diesel fuel;

5) lack of standards for its use, storage and safety.

According to the method of production, hydrogen is divided into:

• "orange", produced by electrolysis using electricity generated by nuclear power plants;

• "green", produced by electrolysis using renewable energy sources (wind, solar, and water energy);

• "blue", produced from hydrocarbons by the gas-vapour conversion method (the generated carbon dioxide is processed and not released into the atmosphere);

• "gray", produced from hydrocarbons by the gas-vapour conversion method (the generated carbon dioxide is released into the atmosphere);

• "turquoise", produced by pyrolysis.

Currently, the least costly method of hydrogen production is vapour conversion, while the most environmentally friendly method is water electrolysis, where the purity of the produced hydrogen is close to 100 %.

If to disregard the environmental impact of electricity generation, such systems are almost harmless, as they only emit hydrogen and oxygen during operation. Methane pyrolysis technology, which generates hydrogen and pure carbon (soot) without releasing it into the atmosphere, is also promising, although it is still in the development stage. Another environmentally friendly method of hydrogen production involves using the biomass reactors.

The most promising sectors for using hydrogen as a means of decarbonization include the mining and metallurgical industries, transportation, and energy. The application of hydrogen fuel cell vehicles has significant potential. At the beginning of 2020, the number of such vehicles exceeded 25,000, with over 12,000 sold in 2019 (Fig. 2) [29].

Hydrogen consumption as a fuel for vehicles could reach approximately 0.4 million tons by 2030, which corresponds to about 0.5 % of current consumption (Fig. 3).

Production, transportation and distribution of hydrogen

A key parameter for batteries or fuel tanks is their power consumption. Hydrogen, regardless of the production method, is relatively low-energy fuel, as it occupies a volume 3,000 times larger than gasoline for the same amount of energy at room temperature. Therefore, gaseous hydrogen must be either compressed (CGH2) or liquefied through cryogenic methods (LH2). To obtain energy equivalent to 1 liter of gasoline, it requires 8 litres of hydrogen compressed at a pressure of 40.53 MPa or 3.73 litres of liquid hydrogen. Although liquid hydrogen has a high energy density, its production process is quite energy-consuming. However, the transportation and filling of liquid hydrogen (LH2) is highly efficient, and the profitability of supplying liquid hydrogen increases proportionally with the growing demand for hydrogen at filling stations.

Hydrogen filling stations

Hydrogen filling stations (HFS) include vehicle refueling devices, compressors, hydrogen storage and cooling systems. To reduce hydrogen evaporation losses during storage, HFSs must be equipped with special thermally insulated cryogenic containers for LH2. HFSs can serve many vehicles, just like regular petrol stations, as the vehicle refueling time is 6–8 min. Optimal calibration of hydrogen filling stations is a complex task due to the fact that hydrogen is provided at the filling station at different pressure levels: high, medium and low, in the range of 35–70 MPa. The higher the pressure provided by the filling station, the more investment for compressors is required (Fig. 4). Additionally, the daily demand, production method and form of hydrogen can vary over time [40].

To enhance the safety of hydrogen storage and use, various options are being considered. Currently, tanks holding hydrogen compressed to 70 MPa contain 5.7 wt.% hydrogen. It is planned to increase the gas density to 7.5 wt.% while reducing costs from $33 per kWh to $8 per kWh. Liquid organic hydrogen carriers (LOHC) achieve a density of 6 wt.% and operate at low pressure, providing increased safety [41].

Solid storage materials, such as metal-organic complexes, metal hydrides, and carbon nanostructures, are also being considered. Their specific energy density (around 3 wt.% hydrogen) is comparable to gas compressed to a pressure of 50 MPa. Since solid storage materials operate at atmospheric pressure, they are much safer than compressed or liquefied hydrogen, significantly increasing their practical applications. Such solid storage materials are already used, for example, in scooters and submarines.

An international scientific group has developed Powerpaste, based on magnesium hydride, which stores ten times more energy than similar lithium-ion batteries [43]. Since the paste is fluid and pumpable, conventional filling equipment can be used for vehicle filling after minor modifications. The cost of such modifications is several tens of thousands of euros, the cost of a high-pressure filling station is 1–2 million euros for a single unit. The paste can be transported in

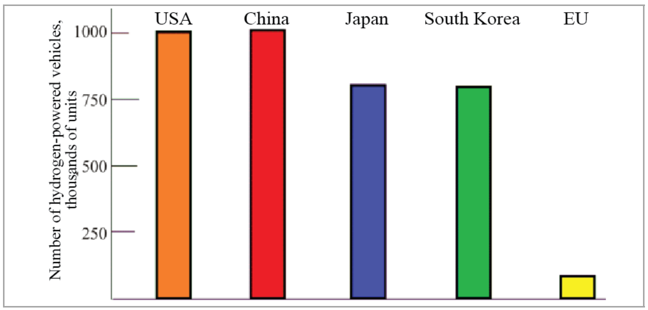

Fig. 2. Structure of the hydrogen vehicle park, thousand units. Forecast for 2030 (according to data [29, 35–39])

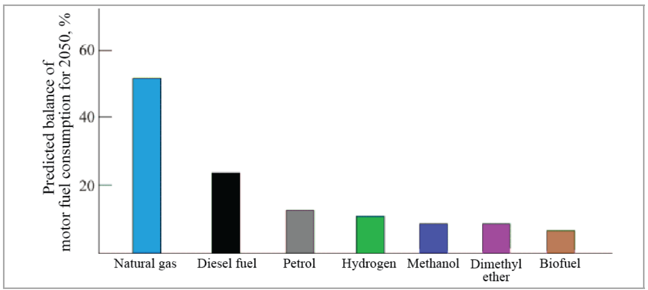

Fig. 3. Predicted balance of motor fuel consumption for 2030–2050

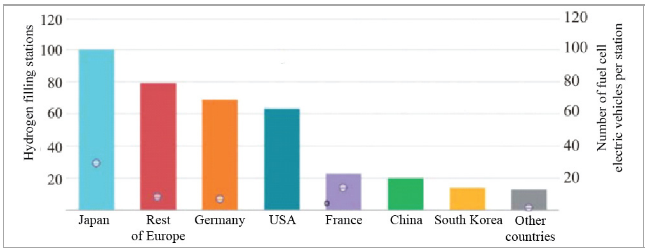

Fig. 4. Hydrogen filling stations and their use, 2018 (based on AFC TCP (2019), AFC TCP Survey on the Number of Fuel Cell Electric Vehicles)

a

b

Fig. 5. Hydrogen-powered equipment: *a* – hydrogen-powered CR240E mining truck by CRRC Yongji company; *b* – JCB hydrogen fuel cell excavator (based on materials from [46])

standard tanks, eliminating the need for cryogenic equipment or expensive high-pressure reservoirs. Filling a vehicle simply requires replacing the paste cartridge and adding some water. Therefore, there is no need in filling stations.

The transition to electric transport will gradually take place, which is ecologically and economically feasible. Currently, such transport uses battery or trolley systems, but they have the following disadvantages: low energy density (for a lithium-ion battery, this is a maximum of 250 watt-hours per kilogram, while heavy-duty electric vehicles require a capacity of at least 600-700 watt-hours per kilogram) and a long battery charging time.

Unlike diesel engines, hydrogen fuel cells operate without vibration and noise, with an average efficiency of 45 % compared to 35 % for diesel engines. A cylinder the size of a standard gasoline tank is enough to cover 500–600 km [40–42]. Additionally, the average lifespan of hydrogen fuel cells is 8 to 10 years, and mass production will inevitably lead to a significant reduction in their cost.

Hydrogen in the mining industry

Mining enterprises consume huge amounts of diesel fuel, which serves as the only energy source for companies operating in remote areas. However, hydrogen energy has the potential to change the situation. Hydrogen can become an energy source for many energy-intensive operations, including:

- loading rock mass into dump trucks or railway cars;
- transportation of rock mass by quarry lorries or railway;
- transportation of personnel by small and medium-sized vehicles.

The main driving force behind the transition to hydrogen-powered operations in underground mining may be the requirement for diesel particulate matter (DPM) levels in the underground environment. Since 2012, the World Health Organization has classified DPM in confined spaces as carcinogenic. As a result, there are two possible options for underground production: increasing ventilation capacity or reducing the amount of DPM emitted by diesel equipment. Following the new regulations will substantially raise ventilation costs. On the other hand, by removing diesel equipment from underground operations, a company can save up to 50 % on ventilation expenses. For a large mining company, it could mean savings ranging from hundreds of thousands to a million dollars annually. Consequently, a gradual shift towards zero-emission heavy equipment using hydrogen fuel cells starts in the mining and construction sectors. The transition not only addresses health and safety concerns but also leads to significant cost reductions and enhances overall operational sustainability.

The mining company Anglo American and the French energy company Engie have announced a partnership agreement to create the first ultra-class fuel cell electric vehicle (UFCEV), a 290-ton hydrogen-powered dump truck. The diesel engine will be replaced with a hydrogen fuel cell module paired with a scalable high-power modular lithium-ion battery system, managed by a high-voltage power distribution unit that provides energy storage of over 1000 kWh. The dump truck is also equipped with a regenerative braking system that allows some energy generated during driving downhill to be returned to the battery [44].

In 2020, the Turkish-Chinese joint venture JMC Heavy Duty Vehicle Co., Ltd presented the JMC Veyron 4×2 FCV hydrogen fuel cell truck with an electric motor with a power of 250 kW and a torque of 1600 N•m. The Chinese engine manufacturer Weichai Power, in collaboration with CRRC Yongji, developed the CR240E, a 200-ton hydrogen fuel cell dump truck with a power capacity of 800 kW. The dump truck

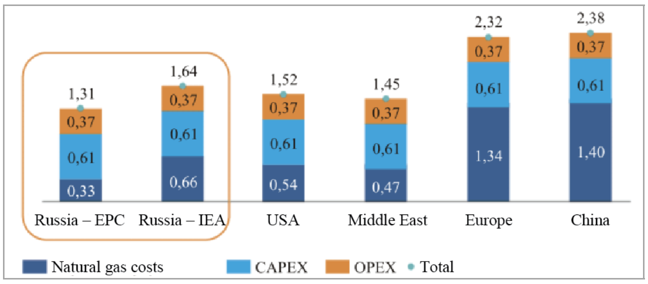

Fig. 6. Cost of hydrogen production from natural gas including costs of carbon capture, storage and utilization" (CCUS), USD/k [47]

has a range of 400 km on a single refueling, with a maximum speed of 85 km/h [45] (Fig. 5, *a*). The dump truck testing in the quarry began at the end of 2021.

The English engineering company JCB, a leader in the zero and low-carbon technologies sector, is already using the 20-ton excavator 220X powered by fuel cells (Fig. 5, *b*). It is the first hydrogen-powered excavator in the construction industry.

In the mining and construction industries, only hydrogen fuel cells provide mobility, power, and safety comparable to diesel, without any emissions. Fuel cell vehicles also offer real environmental advantages: they do not emit diesel fumes, making the workplace cleaner, especially in underground mines.

As hydrogen is regarded as an alternative to fossil fuels, mining companies can redirect their renewable energy resources towards hydrogen production, which could become a sustainable revenue source. Although there are still significant obstacles to overcome before a broader hydrogen economy is established, these challenges are less pronounced for the mining industry than for many other sectors. Mining companies have the opportunity to change the public opinion regarding the environmental protection and to kick-start the global hydrogen economy.

Problems and prospects for the development of hydrogen energy in Russia

In the Energy Strategy of the Russian Federation for the period until 2035 (ES-2035), hydrogen energy is identified as one of the promising areas for development. In October 2020, an action plan ("roadmap") for the development of hydrogen energy in the Russian Federation until 2024 was approved. The plan includes the formation and execution of state support measures for projects, improvement of the regulatory in the field of hydrogen energy, conducting R&D, and strengthening the positions of Russian companies in hydrogen sales markets. The State Corporation "Rosatom" and PJSC "Gazprom" planned to create several pilot low-carbon hydrogen production facilities and develop a prototype of hydrogen-powered railway transport. Currently, Russian Railways (RZD) and "Transmashholding" purchase small hydrogen-powered locomotives abroad and jointly with "Rosatom" establish a hydrogen cluster in Sakhalin. GAZ and "Avtotor" plan to produce hydrogen trucks and automobiles, while KamAZ is focused on hydrogen buses. It is noteworthy that hydrogen electric transport, including rail transport, can already be economically justified even without significant government support. For example, fifteen large hydrogen-powered locomotives have been in operation in Germany for several years, and hydrogen buses have been running in Europe for twenty years. There are also a sufficient number of filling stations for their supply.

Although the EU Hydrogen Strategy prioritizes "green" hydrogen produced from renewable energy sources, it is still possible to use hydrogen from low-carbon energy sources, including fossil fuels combined with CCS technologies. For Russia, the production of "carbon-free" or "carbon-neutral" hydrogen based on electricity generated from hydropower plants, nuclear power plants, renewable energy source power plants, and traditional energy carriers along with CCS technologies is of interest.

According to the IEA and CENEF, hydrogen in Russia is mainly produced and used in the chemical, petrochemical, and refining industries, which corresponds to the global demand for hydrogen. The prospects for hydrogen energy development in Russia, according to the Plan and ES-2035, are currently aimed at hydrogen exports. At the same time, according to ES-2035, Russia aims to be among the global leaders in hydrogen exports, targeting 2.2 billion m^3 by 2024 and 22.2 billion m^3 by 2035. According to Rosstat, hydrogen production in Russia has tripled since 2010, reaching 1.95 billion m^3 in 2019.

The decline in demand for raw materials due to COVID-19 prompted the largest consumers of Russian energy resources (mainly the EU and China) to force their decarbonization plans. The production and use of hydrogen help reduce CO2 emissions and comply with the business models of oil and gas companies. Among Russian companies, "NOVATEK" is prepared to enter the hydrogen market, as its customers are the same as those for LNG. "NOVATEK" plans to produce and export "blue" and "green" hydrogen. The first hydrogen production facility will be launched at the existing "Yamal LNG" project, where hydrogen can be exported to Asia and Europe. For project execution, the construction of wind farms is planned in all regions where the company operates (in Yamal, Gydan, Kamchatka, and the Murmansk region).

Hydrogen transportation can be carried out using the available gas transportation infrastructure. Pilot projects are already being implemented by European gas companies, such as Snam (Italy), National Grid and Northern Gas Networks (UK) together with Equinor.

Selling hydrogen to end consumers, for example, owners of fuel cell electric vehicles, is also a potentially attractive segment that can be developed by oil and gas companies using their existing filling station networks. Total, Shell and Austrian OMV AG are participating in the European H2Mobility project, which aims to develop hydrogen filling infrastructure. As of October 2020, the project operates 115 hydrogen filling stations, 50 more are expected to open [48].

Conclusion

The mining industry is energy-intensive and the main supplier of raw materials for other industries, as well as a major source of global greenhouse gas emissions due to the petroleum fuels. The mining industry has an important feature as it not only supplies materials but also consumes fuel to support the development of the hydrogen economy.

At the same time, the mining sector has various options for reducing carbon emissions and capitalizing on energy cost savings. These options include enhancing energy efficiency measures, expanding energy recovery systems, and using hydrogen to meet electricity, transportation, and heating needs. However, these clean energy alternatives face challenges and largely remain underutilized in the mining sector.

The main trends and issues influencing the mining industry and increasing interest in replacing petroleum fuels are:

1) the depletion of rich and easily accessible ores led to the necessity of extracting, loading, transporting, and processing more materials, which requires significant energy expenditures and, consequently, new investments in energy services;

2) price changes for energy and minerals;

3) growing political and social concern about the environment, reducing the dependence on fossil fuels and improving the social and environmental performance of mining and processing plants.

The hydrogen energy, which can be stored and used for power generation, transportation of rock mass and heating, is of interest to the mining industry. Thus, the potential of using hydrogen as a replacement for fossil (diesel) fuel may solve some of the listed key challenges that the mining industry faces.

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Funding: The study had no sponsorship support.
Conflict of interest. The authors declare no conflict of interest.
The authors' contribution is equal.