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THE CHALLENGE OF REDUCING DIESEL CONSUMPTION AND GREENHOUSE GAS EMISSIONS: A PERSPECTIVE ON THE USE OF HYDROGEN IN MINING TRUCKS

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Abstract: In mining, the traditional system of operation relies on equipment that consumes large amounts of energy. In mine operations, trucks are widely used due to their flexibility, loading capacity, and adaptability to various terrain conditions. However, they have high diesel oil consumption and high emission rates of smoke, particulate matter, and mainly carbon gas from diesel engines. This article offers a comprehensive view on the effect of hydrogen added to the diesel engine in the search for renewable energy alternatives that are in tune with the reduction of the environmental impact arising from the use of petroleum-derived fuels. The article presents an overview about the challenges in reducing the diesel fuel consumption of trucks employed in mining. It approaches the effect of controlled hydrogen addition on diesel engine performance, consumption reduction, and greenhouse gas emissions. Followed by a discussion of the main technologies used to manufacture hydrogen and their production costs. The results of the studies show that hydrogen is a promising alternative for reducing operational, energy, and emissions costs, mainly carbon dioxide (CO_2) and carbon monoxide (CO), but it faces barriers in production, storage, and supply costs. We highlight the "green hydrogen", carbon-free, which contributes to the decarbonization process in mines, as open pit or underground ones.

***Keywords*:** *diesel oil, hydrogen, consumption, emissions, decarbonization*

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1. INTRODUCTION

Mining is present all over the world, but only a few countries, adequately, enjoy these potential and riches. These countries have become leaders in methods and technologies for exploiting mineral resources (Yellishetty et al. 2021).

In Brazil, the mining sector has a prominent position in the world scenario, as it is one of the main exporters of iron ore. Iron ore is the main mining commodity in Brazil (Câmara et al. 2019). The country stands out for having representative reserves of this ore, corresponding to approximately 19% of the production in the world (ANM, 2022).

In open pit iron ore extraction, several diesel-powered pieces of equipment are present (Giuliano et al. 2021). Featured for transport trucks that have low-speed torque and high power density (Symonenko et al. 2019). The main disadvantages are high fuel consumption, high carbon dioxide emission rate, and high maintenance cost (Reitz et al. 2020).

In underground mining, challenges related to diesel-powered equipment include issues with combustion gas emissions, limited visibility, risks to worker health, and the need for intensive ventilation. Freire et al. (2023) emphasize that the electrification of such equipment, such as Load Haul Dumps (LHDs), can lead to a significant improvement in energy efficiency compared to diesel models. In their study, they introduced an electromechanical model to assess this efficiency, revealing that a 14-ton electric LHD consumed 60.5% less energy than a diesel-powered LHD. This substantial difference underscores the benefits of electrification in reducing energy consumption and greenhouse gas emissions in the operation of underground loading and transport equipment.

One of the challenges associated with fossil fuel-based engines is gas emissions, including carbon monoxide, carbon dioxide, hydrocarbons, particulate matter, and nitric oxides, which directly impact the environment (Golbasi and Kina 2022).

Thus, the intensive consumption of diesel oil motivates the search for renewable energy alternatives that are in tune with the reduction of the environmental impact arising from the use of fuels derived from petroleum (Gunawan and Monaghan 2022). The Hydrogen Economy stands out among the possibilities of using renewable energies (Fan et al. 2021).

Moreover, hydrogen is considered the best candidate as an additive to be added to diesel because it is a renewable source that meets the required engine characteristics (Benbellil et al. 2022). Most electrified engines use batteries that are composed of lithium, a non-renewable mineral, so the addition of hydrogen becomes feasible, especially in hybrid equipment, combining two different types of fuel (Beltrami et al. 2021).

According to Fan et al. (2021), the addition of hydrogen to conventional petroleum-derived fuels has been recommended as a method to improve performance as well as reduce emissions.

Adding small amounts of hydrogen to a diesel engine increases brake thermal efficiency (BTE), reduces the heterogeneity of the fuel spray within the combustion chamber resulting from high diffusivity, and allows the mixture to become homogeneous, i.e., one premixed with air, thus having more uniformity (An et al. 2013).

This paper covers a review on the effect of adding hydrogen to diesel-powered engines and its relation to consumption and emissions. It discusses energy consumption in open pit or underground mining, as well as hydrogen production technologies. Green hydrogen, carbon-free, is an alternative in the decarbonization process in mining.

2. ENERGY CONSUMPTION IN OPEN PIT MINING

In open pit mines, the traditional dispatch system is based on truck transportation, which consumes large amounts of energy in the transportation sector during mine operations (Giuliano et al. 2021). The transportation cost can be approximately 50% of the total operating cost in medium or large mines (Bajany et al. 2019).

Trucks are commonly employed in open pit mines for loading, and hauling ore and waste rock due to their flexibility and ability to transport material over complex terrain (Bajany et al. 2019). The operational flexibility and large capacity of trucks have made them popular in mines. On the other hand, 40% of the energy consumed in a mine comes from diesel, and despite recent improvements in truck efficiency, they are still the largest consumers in mining (Vilaça et al. 2022). Other operations that need large electricity are grinding and ventilation.

In addition to emitting large volumes of greenhouse gases, this equipment has been a challenge for the mining industry due to the associated environmental damage. For example, an average off-highway truck consumes an annual rate of 14.89 million gallons of diesel fuel, therefore, it emits about 47 810.60 kg of greenhouse gases each year (Gholami et al. 2022).

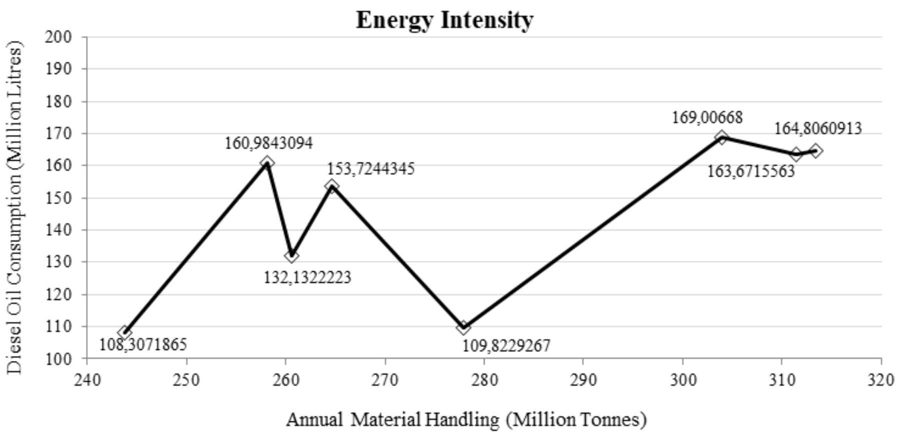

Fig. 1. Energy Intensity (Adapted from ANM, 2022)

The energy intensity of moving materials in open pit mine operations consumes large amounts of diesel oil (Symonenko et al. 2019). Figure 1 correlates the movement of extracted materials and diesel oil consumption in the scenario of an open pit ferrous mine in northern Brazil (ANM 2022).

Figure 1 shows a variation in the behavior of diesel consumption, where some variables are significant, which depend mainly on the production process, the depth of the mines, and the elevation of the stockpiles. Note how of diesel consumption in liters per ton is directly correlated to the increase in material handling.

2.1. FACTORS THAT AFFECT FUEL CONSUMPTION AND EMISSIONS

The fuel consumption behavior and resulting carbon emissions of a dispatch system can be affected by several factors (Wang et al. 2021). According to Runge (1998), the fuel consumption of an off-highway truck can be estimated by the empirical formula.

$$F_C = P \cdot 0.3 \cdot L_F, \tag{1}$$

where: F_C is the fuel consumption [L/h], P is the power demand [kW], 0.3 is the unit conversion factor [L/kW/h], and L_F is the load factor provided by the manufacturer.

In order to understand fuel consumption in haulage operations in a mine, one should not limit oneself to the mechanical characteristics of haulage trucks. It is necessary to evaluate the influence of other factors in the production process (such as route, topographical conditions, mainly the increase in pit depth, the elevation of waste piles, weather conditions, types of trucks used in operations, traffic, and work profile of the drivers), presented in Fig. 2 (Golbasi et al., 2022).

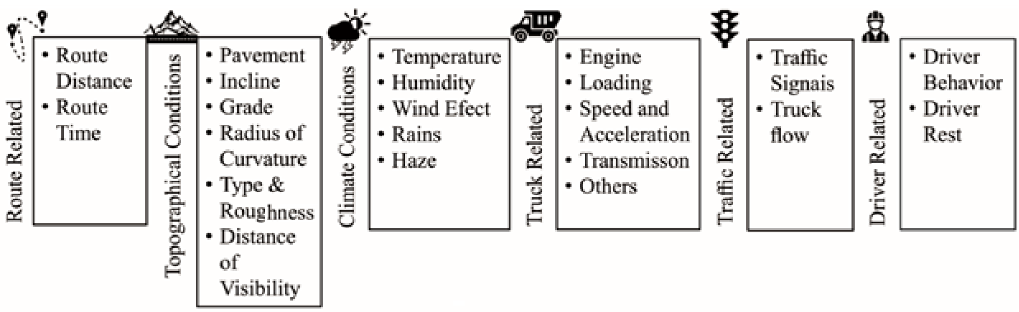

Fig. 2. Factors affecting fuel consumption of trucks (Author's own elaboration, 2023)

The factors presented in Fig. 2 directly or indirectly affect diesel consumption and exhaust gas emissions. Depending on production capacity, pit layout, and material movement, diesel consumption increases, as do carbon dioxide and particulate matter emissions (Dindarloo and Siami-Irdemoosa 2016).

Autonomous trucks in mining represent a significant advancement in reducing fossil fuel consumption and greenhouse gas emissions. Managed by advanced computer systems, GPS, radar, and artificial intelligence, these trucks travel routes between the mining face and the dumping area. Optimized in real-time, these vehicles ensure operational efficiency of up to 40%, according to Mining Technology Solutions (Modular Mining). This efficiency translates into cost reduction, such as fuel, gas emissions, and tire costs, as well as increased productivity (Wang et al. 2023).

Additionally, autonomous trucks can operate continuously, without shift breaks, optimizing vehicle usage and enhancing overall mining productivity (Zhang et al. 2023). Several mining truck manufacturers, such as Caterpillar, Volvo, and Komatsu, have made significant strides in introducing autonomous trucks and developing unmanned material transportation systems. Caterpillar, for instance, had over 500 autonomous trucks in operation worldwide (Caterpillar 2022). The most popular models, including Caterpillar 793F, 789C, 793D, and 789D, have been deployed in open-pit mines in Australia, Brazil, and the USA. Similarly, the Japanese manufacturer Komatsu has deployed over 400 autonomous trucks in open-pit mines worldwide, transporting more than 3 billion tons of materials (Smsequipment, 2022).

Implementing autonomous trucks in open-pit mining faces significant challenges such as high initial investment and long-term financial return. Issues related to infrastructure, detailed mapping, safety, organizational culture, training, maintenance, and technical support also arise. To operate efficiently and safely, precise mapping of roads, loading and maneuvering areas is necessary, along with ensuring a robust communication and power infrastructure. Autonomous trucks must also safely interact in shared environments with human operators, effectively detecting and avoiding obstacles (Huo et al. 2022).

Hydrogen is considered a renewable, carbon-free energy source, presenting a viable alternative when combined with fossil fuels. In controlled amounts, it can be used as a secondary fuel alongside diesel, promoting more efficient combustion, reducing consumption, and greenhouse gas emissions.

3. EFFECT OF HYDROGEN ADDITION

The use of hydrogen as a fuel is challenging because of the difficulties in production, storage, transportation, and supply (Ally et al. 2015).

However, the use of hydrogen as an additive in fossil fuels is presented as a viable alternative (Di Ilio et al. 2021). In small quantities, hydrogen can be used as a secondary fuel with diesel to assist in the combustion process (Kenanoğlu et al. 2020).

Hydrogen is indicated as an additional fuel in diesel-fueled compression ignition engines due to its characteristics and properties shown in Table 1 compared to diesel (Krishnasamy et al. 2021).

It can be noted in Table 1 that hydrogen has a wide flammability range, from 4 to 75%, in comparison with diesel oil, and a higher ignition speed, which allows the engines to run with poorer mixtures, that is, with less diesel injection.

Table 1. Properties of Diesel and Hydrogen (Jamrozik et al., 2020)

Property	Diesel	Hydrogen
Molar mass [kg/km]	100.2	2015
Autoignition temperature in air [K]	530	858
Density [kg/m^3]	837.0	0.089
Flame velocity (φ = 1) [ms^{-1}]	0.3	2.75
Flammability limits (% vol. in the air)	0.7–5	4–75
Stoichiometric *A*/*F* ratio	15.16	34.273
The heat of evaporation [KJ/kg]	275.0	46.0

The hydrogen-air mixture can be easily ignited in compression ignition engines because the minimum ignition energy is lower than that of diesel (Benbellil et al. 2022). The main benefit of using hydrogen over other petroleum-based fuels is that the by-product of its complete combustion is water (Anon 2018).

Table 2. Summary of previous studies current to this paper

Subject of study	Author
1D energy, energy, and performance assessment of turbocharged diesel/hydrogen RCCI engine at different levels of diesel, hydrogen, compressor pressure ratio, and combustion duration	Taghavifar et al. 2021
Detailed performance and CO_2 emission analysis of a very large crude carrier propulsion system with the main engine running on dual fuel mode using hydrogen/diesel versus natural gas/diesel and conventional diesel engines	Gholami et al. 2022
An economic evaluation of fuel cell-powered off-road machinery using stochastic analysis	(Reyes-Valenzuela et al. 2022)
Experimental analysis of the performance, and combustion/emission characteristics of a DI diesel engine using hydrogen in dual fuel mode	(Bakar et al. 2022)
Experimental investigations on performance, emission, and combustion characteristics of Diesel-Hydrogen and Diesel-HHO gas in a dual fuel CI engine	(Subramanian and Thangavel 2020)
Hydrogen effects on combustion stability, performance, and emission of diesel engines	(Jamrozik et al. 2020)
Green hydrogen standard in China: Standard and evaluation of low-carbon hydrogen, clean hydrogen, and renewable hydrogen	(Hermesmann and Müller 2022)
Investigation of natural gas enrichment with high hydrogen participation in dual fuel diesel engine	(Benbellil et al. 2022)
Low-load hydrogen-diesel dual-fuel engine operation – A combustion efficiency improvement approach	(Dimitriou et al. 2019)

Table 2 presents a general review on the effect of hydrogen addition in diesel engines from previous studies related to the present article.

The following results are highlighted.

- Factor Improvement, such as the thermal efficiency, the effective average power, pressure, and the specific energy consumption.
- Reduction of unburned hydrocarbons, carbon monoxide, carbon dioxide, and particulates. However, there is an increase in NOX when adding hydrogen due to the high combustion temperature inside the chamber.
- The adaptability of the diesel engine and insensitive to fuel type make it a viable candidate for converting to a bi-fuel engine with few changes and without major costs.
- A carbon-free fuel, on combustion, produces a significant amount of energy by releasing water vapor.

3.1. CO_2 EMISSIONS FROM MINING TRUCKS

Currently, CO_2 measurements in off-road mining trucks are carried out in various ways. One of them is through emission factors, which are determined based on fuel consumption and engine characteristics. These factors help estimate CO_2 emissions based on the vehicle's activity, such as the amount of material transported.

For Soofastaei et al. (2016), the CO_2 emissions from diesel fuels can be calculated by the amount of fuel consumed, through Eq. (2).

$$CO_2 \text{ emissions} = F_C \cdot E_F, \quad (2)$$

where F_C represents the diesel fuel consumption [L/h] and E_F is the CO_2 emission factor, equivalent, on average, to 2.70 kilograms of CO_2 emitted per liter of burned diesel oil.

Another technique is the use of Portable Emission Measurement Systems, which can be used to measure emissions directly from the trucks' exhaust. These systems are portable and can be used in the field to collect data on CO_2 emissions under real operating conditions.

Carvalho et al. (2022) highlights in his research the measurement of CO_2 emissions for four types of off-road trucks. For this purpose, the concentrations of gases in the exhaust were measured using direct sampling with a portable analyzer. These measurements were taken under different operating conditions of the trucks, including trucks at rest, i.e., idling (during shift changes, loading, unloading, and waiting in line) and in motion (with and without load). The results revealed that off-road mining trucks at rest during shift changes, loading, unloading, and waiting in line. The average CO_2 emission factors can be as low as 64.8% of the standard value from the Intergovernmental Panel on Climate Change (IPCC) for diesel fuel. This means that, on average, trucks at rest emit only about two-thirds of the expected CO_2 based on IPCC estimates.

The studies demonstrate that off-road trucks are a significant source of CO_2 emissions, highlighting the importance of developing strategies to reduce these emissions. According to Kumar, and Lata (2023) show evidence of reduced emissions of gases, especially CO, CO_2, HC, and particulate matter with the addition of hydrogen.

The study focuses on the Mogalakwena Mine, operated by Anglo American Platinum in South Africa, which has set a target of net zero emissions by 2040, the most ambitious in the sector. Part of the strategy involves the development of green hydrogen, produced through water electrolysis using renewable and carbon-free energy sources.

This is important due to green hydrogen's ability to decarbonize the mining industries. Anglo American's latest step is to prepare its mines for the introduction of hydrogen-powered trucks. The off-road truck model 930E, manufactured by Komatsu, is powered by hydrogen fuel cells and also operates with a lithium battery. The total operating cost of these trucks will be comparable to diesel by 2030. It is estimated that these new trucks will allow a significant reduction of 50% to 70% in emissions (Cole, 2023).

4. DISCUSSION – PERSPECTIVES AND CHALLENGES

In the transition to a clean energy future, mining companies will need to decarbonize not only to meet emissions reduction targets, but also to comply with increasingly stringent environmental regulations established by multilateral agreements between countries (Calvo and Valero 2022). Although, most industries have committed to moving towards carbon neutrality by 2050 (Müller-Casseres et al. 2021).

In order to achieve the emission reduction targets, the so-called "Hydrogen Economy" stands out. The term refers to an energy resource based on the use of hydrogen in larger proportions to substitute fossil fuels. Furthermore, it is presented as a viable alternative because the direct combustion of hydrogen produces a significant amount of energy and the main by-product of its complete combustion is water (Santos et al. 2020).

The mining industry has the prospect of being directly impacted by the hydrogen economy, which will modify the energy matrix of the energy sources of diesel-powered equipment that would result in decreased carbon levels (Gunawan and Monaghan, 2022).

Hydrogen can be obtained by various methods, in which, the five main technologies in hydrogen production, gray, blue, green, brown, and yellow, stand out, as shown in Fig. 3 (Ajanovic et al. 2022).

Figure 3 summarizes the color scheme into five main forms of hydrogen production: (i) Green Hydrogen – obtained by electrolysis of water using renewable sources of its generation; (ii) Gray Hydrogen – obtained by steam reforming of methane; (iii) Blue Hydrogen – obtained from fossil sources, but captures and stores the CO_2 produced in the process (SMR); (iv) Brown Hydrogen – obtained by gasification of coal, and (v) Yellow Hydrogen – obtained by electrolysis of water employing electricity generated from different energy sources.

Table 3 presents the technologies associated with hydrogen production by the color scheme shown in Fig. 3.

Note in Table 3 that each technology is associated with a color, specifying the raw material, production technology, and CO_2 emissions.

Table 3. Estimated costs for hydrogen production models (Adapted from Hermesmann and Muller 2022).

Associated color	Primary feedstock	Technology	Process-related CO_2 emissions	Source
Green	Water	Polymer electrolyte membrane electrolysis	Carbon – free	Lumbers, Barley, and Platte 2022
Gray	Natural Gas	Steam methane reforming	High – CO_2	Oni et al. 2022
Blue	Natural Gas	Steam methane reforming with capture and storage	CO_2 – free	Ajanovic et al. 2022
Brown	Natural Gas	Coal gasification without carbon capture, utilization, and storage (CCS)	High – CO_2	Ajanovic et al. 2022
White	Water	Alkaline electrolysis (ALK) and solid oxide electrolyzer cell (SOEC)	Carbon – free	Lumbers et al. 2022

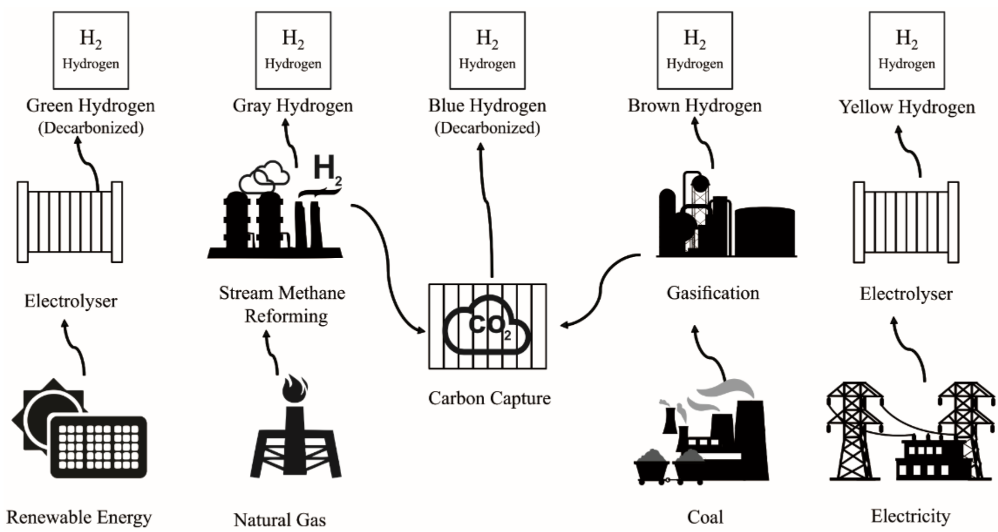

Fig. 3. Differentiation of the five main forms of hydrogen production
(Author's own elaboration, 2023)

The production of “green” hydrogen stands out, because it is produced by electrolysis of water using renewable energy sources.

Figure 4 presents the cost estimate for hydrogen production technologies. According to the hydrogen production method, Fig. 4 shows the final hydrogen generation costs (Ajanovic et al. 2022).

Research points out the challenges in adapting to dynamic operation for hydrogen generation: storage, production, and supply (Sinigaglia et al. 2017).

Hydrogen storage entails another major challenge: developing compact, reliable, economical, and safe systems. Scientists are looking for viable alternatives, such as different types of materials, but bump into costs (Fúnez Guerra et al. 2020).

According to Qyyum et al. (2021), storing hydrogen in 100 kW compressors has an average cost of USD 1054 – USD 1580/kW; for tanks smaller than 50 kW, the costs rise to USD 5267/kW.

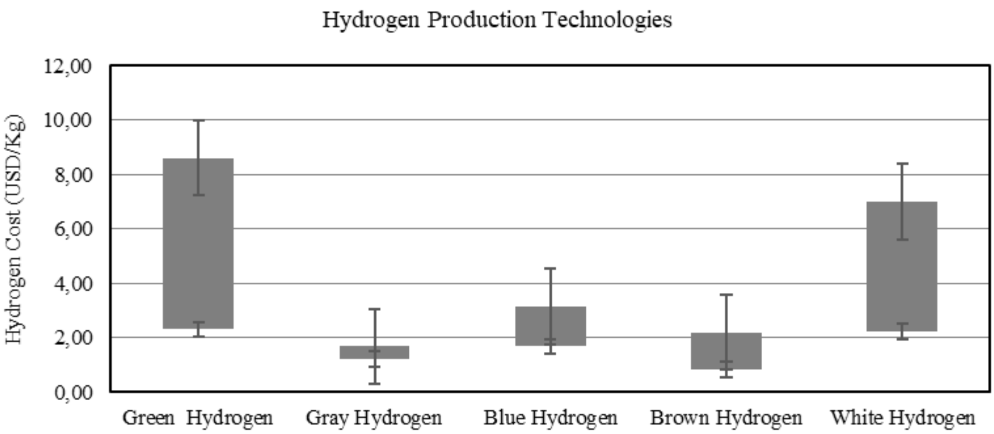

Fig. 4. Costs of Hydrogen production technologies
(Adapted from Ajanovic et al. 2022).

5. CONCLUSION

Mining is one of the most resource-intensive industries, relying heavily on fossil fuels, especially for the loading and transportation of ore, as well as overburden or even tailings, using heavy equipment to move these materials. The mining industries are seeking new technologies to meet new environmental impact regulations, especially regarding gas emissions. The “Hydrogen Economy” presents itself as a promising technology; however, several aspects need advancement:

- Widening the adoption of the “Hydrogen Economy” technology to increase production capacity and reduce costs.

- Ensuring the generation, storage, production, and supply of hydrogen along a production chain.
- Advancing in hydrogen storage and safety.
- Providing incentives for research and development projects in "Hydrogen Economy" technology for industries.

The potential of hydrogen, derived from renewable and carbon-free energy sources, stands out as an emerging alternative for the decarbonization of the mining industry, being able to be combined in a controlled manner with fossil fuels or used in electrified vehicles. Although considered a viable solution for reducing emissions in mining, it is essential to overcome challenges related to the production, storage, supply, safety, and cost of hydrogen.

For future research, a more comprehensive analysis of hydrogen utilization opportunities in the mining sector can be conducted, considering technical, economic, and environmental aspects. The lack of cost projections and assessments of hydrogen implementation in the context of mining companies is a gap identified in the literature. Highlighting hydrogen as a potential candidate for mining companies, providing relevant information on opportunities and challenges, is also important.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that may have influenced the work reported in this article.

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REFERENCES

AJANOVIC A., SAYER M., and HAAS R., 2022, *The Economics and the Environmental Benignity of Different Colors of Hydrogen*, International Journal of Hydrogen Energy, DOI: 10.1016/j.ijhydene.2022.02.094.

ALLY J., PRYOR T., and PIGNERI A., 2015, *The Role of Hydrogen in Australia's Transport Energy Mix*, International Journal of Hydrogen Energy, 40 (13), 4426–4441, DOI: 10.1016/j.ijhydene.2015.02.022.

AN H., Yang W.M., MAGHBOULI A., LI J., CHOU S.K., and CHUA K.J., 2013, *A Numerical Study on a Hydrogen Assisted Diesel Engine*, International Journal of Hydrogen Energy, 38 (6), 2919–2928, DOI: 10.1016/j.ijhydene.2012.12.062.

ANM, 2022, *Brazilian Mineral Yearbook: Main Metallic Substances*, https://Www.Gov.Br/Anm/Pt-Br/Centrais-de-Conteudo/Publicacoes/Serie-Estatisticas-e-Economia-Mineral/Anuario-Mineral/Anuario-Mineral-Brasileiro/Amb-2021-Ano-Base-2020.Pdf. (Accessed 30 June 2022).

Anon, 2018, *A Study on the Effects of Combined Diesel-Hydrogen Combustion on Diesel Engines Using Experimental and Simulation Techniques*.

BAJANY D.M., ZHANG L., and XIA X., 2019, *An Optimization Approach for Shovel Allocation to Minimize Fuel Consumption in Open-Pit Mines: Case of Heterogeneous Fleet of Shovels*, [in:] *IFAC-PapersOnLine*, Vol. 52, Elsevier B.V., pp. 207–212.

BAKAR R.A., KADIRGAMA WIDUDO K., RAMASAMY D., TALAL YUSAF, KAMARULZAMAN M.K., SIVARAOS NAVID ASLFATTAHI, SAMYLINGAM L., and ALWAYZY SADAM H., 2022, *Experimental Analysis on the Performance, Combustion/Emission Characteristics of a DI Diesel Engine Using Hydrogen in Dual Fuel Mode*, International Journal of Hydrogen Energy, DOI: 10.1016/j.ijhydene.2022.04.129.

BELTRAMI D., IORA P., TRIBIOLI L., and UBERTI S., 2021, *Electrification of Compact Off-Highway Vehicles – Overview of the Current State of the Art and Trends*, Energies, 14 (17), 1–29, DOI: 10.3390/en14175565.

BENBELLIL MESSAOUD ABDELALLI, MOHAND SAID LOUNICI, KHALED LOUBAR, and MOHAND TAZEROUT, 2022, *Investigation of Natural Gas Enrichment with High Hydrogen Participation in Dual Fuel Diesel Engine*, Energy, 243, DOI: 10.1016/j.energy.2021.122746.

CALVO G., and VALERO A., 2022, *Strategic Mineral Resources: Availability and Future Estimations for the Renewable Energy Sector*, Environmental Development, DOI: 10.1016/j.envdev.2021.100640.

CÂMARA R., CÂMARA G., ANDRADE NETO M., MILOSEVIC T., CÉLIO ANDRADE J., and ROCHA P., 2019, *Reserve Assessment and Certification of Brazil's Oil and Mineral Sectors and Energy Storage: New Trends, Analysis, and Regulatory Proposals*, Resources Policy, 62 (August 2018), 347–356, DOI: 10.1016/j.resourpol.2019.04.003.

CARVALHO Jr. J.A., DE CASTRO A., BRASIL G.H., DE SOUZA Jr. P.A., and MENDIBURU A.Z., 2022, *CO_2 Emission Factors and Carbon Losses for Off-Road Mining Trucks*, Energies, 15 (7), 2659.

CATERPILLAR, 2022, *Autonomous trucks operating worldwide with cat® command for hauling*, https://www.caterpillar.com/en/news/caterpillarNews/2022/500-autonomous-trucks.html [Accessed: 04 March 2024].

COLE M.J., 2023, *ESG risks to global platinum supply: A case study of Mogalakwena Mine, South Africa*, Resources Policy, 85, 104054.

DIMITRIOU P., Tsujimura T., and SUZUKI Y., 2019, *Low-Load Hydrogen-Diesel Dual-Fuel Engine Operation – A Combustion Efficiency Improvement Approach*, International Journal of Hydrogen Energy, 44 (31), 17048–17060, DOI: 10.1016/j.ijhydene.2019.04.203.

DINDARLOO S.R. and SIAMI-IRDEMOOSA E., 2016, *Determinants of Fuel Consumption in Mining Trucks*, Energy, 112, 232–240, DOI: 10.1016/j.energy.2016.06.085.

DUARTE SOUZA ALVARENGA SANTOS N., RODRIGUES FILHO F.A., TEIXEIRA MALAQUIAS A.C., and COELHO BAÊTA J.G., 2020, *Study of the Water Injection Control Parameters on Combustion Performance of a Spark-Ignition Engine*, Energy, 212.

DI ILIO G., DI GIORGIO P., TRIBIOLI L., BELLA G., and JANNELLI E., 2021, *Preliminary Design of a Fuel Cell/Battery Hybrid Powertrain for a Heavy-Duty Yard Truck for Port Logistics*, Energy Conversion and Management, Vol. 243, DOI: 10.1016/j.enconman.2021.114423.

FAN LIXIN, ZHENGKAI TU, and SIEW HWA CHAN, 2021, *Recent Development of Hydrogen and Fuel Cell Technologies: A Review*, Energy Reports, 7, 8421–8446.

FREIRE G., RAMIREZ G., GÓMEZ R., SKRZYPKOWSKI K., and ZAGÓRSKI K., 2023, *Electro-Mechanical Modeling and Evaluation of Electric Load Haul Dump Based on Field Measurements*, Energies, 16, No. 11, 4399, DOI: 10.3390/en16114399.

FÚNEZ GUERRA C., REYES-BOZO L., VYHMEISTER E., JAÉN CAPARRÓS M., SALAZAR J.L., GODOY-FAÚNDEZ A., CLEMENTE-JUL C., and VERASTEGUI-RAYO D., 2020, *Viability Analysis of Underground Mining Machinery Using Green Hydrogen as a Fuel*, International Journal of Hydrogen Energy, 45 (8), 5112–5121, DOI: 10.1016/j.ijhydene.2019.07.250.

GHOLAMI ABOOZAR, SEYED ALI JAZAYERI, and QADIR ESMAILI, 2022, *A Detail Performance and CO2 Emission Analysis of a Very Large Crude Carrier Propulsion System with the Main Engine Running on Dual Fuel Mode Using Hydrogen/Diesel versus Natural Gas/Diesel and Conventional Diesel Engines*, Process Safety and Environmental Protection, 163 (May), 621–635, DOI: 10.1016/j.psep.2022.05.069.

GIULIANO G., DESSOUKY M., DEXTER S., FANG J., HU S., and Miller M., 2021, *Heavy-Duty Trucks: The Challenge of Getting to Zero*, Transportation Research Part D: Transport and Environment, 93, DOI: 10.1016/j.trd.2021.102742.

GOLBASI O. and KINA E., 2022, *Haul Truck Fuel Consumption Modeling under Random Operating Conditions: A Case Study*, Transportation Research Part D: Transport and Environment, 102, DOI: 10.1016/j.trd.2021.103135.

GUNAWAN TUBAGUS ARYANDI, and MONAGHAN R.F.D., 2022, *Techno-Econo-Environmental Comparisons of Zero- and Low-Emission Heavy-Duty Trucks*, Applied Energy, 308, DOI: 10.1016/j.apenergy.2021.118327.

HERMESMANN M., and MÜLLER T.E.. 2022, *Green, Turquoise, Blue, or Grey? Environmentally Friendly Hydrogen Production in Transforming Energy Systems*, Progress in Energy and Combustion Science, Vol. 90 (August 2021),100996, DOI: 10.1016/j.pecs.2022.100996.

HUO D., SARI Y.A., and ZHANG Q., 2024, *Smart dispatching for low-carbon mining fleet: A deep reinforcement learning approach*, Journal of Cleaner Production, Vol. 35, p. 140459, DOI: 10.1016/j.jclepro.2023.140459.

JAMROZIK A., GRAB-ROGALIŃSKI K., and TUTAK W., 2020, *Hydrogen Effects on Combustion Stability, Performance and Emission of Diesel Engine*, International Journal of Hydrogen Energy, 45 (38), 19936–19947, DOI: 10.1016/j.ijhydene.2020.05.049.

KENANOĞLU R., BALTACIOĞLU M.K., DEMIR M.H., and ÖZDEMIR M.E., 2020, *Performance and Emission Analysis of HHO Enriched Dual-Fuelled Diesel Engine with Artificial Neural Network Prediction Approaches*, International Journal of Hydrogen Energy, 45 (49), 26357–26369, DOI: 10.1016/j.ijhydene.2020.02.108.

KRISHNASAMY A., GUPTA S.K., and REITZ R.D., 2021, *Prospective Fuels for Diesel Low Temperature Combustion Engine Applications: A Critical Review*, International Journal of Engine Research, 22 (7), 2071–2106.

KUMAR A., LATA D.B., 2023, *Investigation on the performance and emissions of tri-ethylene glycol mono methyl ether with hydrogen as a secondary fuel in dual fuel diesel engine*, International Journal of Hydrogen Energy, Vol. 48, No. 26, pp. 9895–9910.

LUMBERS B., BARLEY J., and PLATTE F., 2022, *Low-Emission Hydrogen Production via the Thermo--Catalytic Decomposition of Methane for the Decarbonization of Iron Ore Mines in Western Australia*, International Journal of Hydrogen Energy, 47 (37), 16347–16361, DOI: 10.1016/j.ijhydene.2022.03.124.

MÜLLER-CASSERES E., CARVALHO F, NOGUEIRA T., FONTE C., IMPÉRIO M., POGGIO M., HUANG KEN WEI, PORTUGAL-PEREIRA J., ROCHEDO P.R.R., SZKLO A., and SCHAEFFER R., 2021, *Production of Alternative Marine Fuels in Brazil: An Integrated Assessment Perspective*, Energy, Vol. 219, DOI: 10.1016/j.energy.2020.119444.

ONI A.O., ANAYA K., GIWA T., DI LULLO G., and KUMAR A., 2022, *Comparative Assessment of Blue Hydrogen from Steam Methane Reforming, Autothermal Reforming, and Natural Gas Decomposition Technologies for Natural Gas-Producing Regions*, Energy Conversion and Management, 254, 115245, DOI: 10.1016/j.enconman.2022.115245.

QAYYUM M.A., DICKSON R., ALI SHAH S.F., NIAZ H., KHAN A., JAY LIU J., and LEE M., 2021, *Availability, Versatility, and Viability of Feedstocks for Hydrogen Production: Product Space Perspective*, Renewable and Sustainable Energy Reviews, 145 (March), 110843, DOI: 10.1016/j.rser.2021.110843.

REITZ R.D., H. PAYRI O.R., FANSLER T., KOKJOHN S., MORIYOSHI Y., AGARWAL A.K., ARCOUMANIS D., ASSANIS D., BAE C., BOULOUCHOS K., CANAKCI M., CURRAN S., DENBRATT I., GAVAISES M., GUENTHNER M., HASSE C., HUANG Z., ISHIYAMA T., JOHANSSON B., JOHNSON T.V., KALGHATGI G., KOIKE M., KONG S.C., LEIPERTZ A., MILES P., NOVELLA R., ONORATI A., RICHTER M., SHUAI S., SIEBERS D., SU W., TRUJILLO M., UCHIDA N., VAGLIECO B.M., WAGNER R.M., and ZHAO H., 2020, *IJER Editorial: The Future of the Internal Combustion Engine*, International Journal of Engine Research, 21 (1), 3–10.

REYES-VALENZUELA M., SÁNCHEZ-SQUELLA A., BARRAZA R., OSSES M., and VALDIVIA--LEFORT P., 2022, *Economic Evaluation of Fuel Cell-Powered OFF-ROAD Machinery Using Stochastic Analysis*, International Journal of Hydrogen Energy, 47 (5), 2771–2782, DOI: 10.1016/j.ijhydene.2021.10.247.

RUNGE I.C., 1998, *Mining economics and strategy*, SME – Society for Mining Metallurgy and Exploration, ISBN: 0873351657.

SINIGAGLIA T., LEWISKI F., SANTOS MARTINS M.E., and MAIRESSE SILUK J.C., 2017, *Production, Storage, Fuel Stations of Hydrogen and Its Utilization in Automotive Applications-a Review*, International Journal of Hydrogen Energy, 42 (39), 24597–24611.

SOOFASTAEI A., AMINOSSADATI S., KNIGHTS P., KIZIL M., 2016, *Comprehensive investigation of loading variance influence on fuel consumption and gas emissions in mine haulage operation*, International Journal of Mining Science and Technology, Vol. 26, No. 6, pp. 995–1001.

SUBRAMANIAN B. and THANGAVEL V., 2020, *Experimental Investigations on Performance, Emission and Combustion Characteristics of Diesel-Hydrogen and Diesel-HHO Gas in a Dual Fuel CI Engine*, International Journal of Hydrogen Energy, 45 (46), 25479–25492, DOI: 10.1016/j.ijhydene.2020.06.280.

SMSEQUIPMENT, 2022, *AHS technology operates globally*, https://www.smsequipment.com/en-ca/advanced-technologies/smart-mining/autonomous-haulage-systems/ [Accessed: 04 March 2024].

SYMONENKO V.I., HADDAD J.S., CHERNIAIEV O.V., RASTSVIETAIEV V.O., and AL--RAWASHDEH M.O., 2019, *Substantiating Systems of Open-Pit Mining Equipment in the Context of Specific Cost*, Journal of The Institution of Engineers (India): Series D, 100 (2), 301–305, DOI: 10.1007/s40033-019-00185-2.

TAGHAVIFAR H., NEMATI A., SALVADOR F.J., and DE LA MORENA J., 2021, *1D Energy, and Performance Assessment of Turbocharged Diesel/Hydrogen RCCI Engine at Different Levels of Diesel, Hydrogen, Compressor Pressure Ratio, and Combustion Duration*, International Journal of Hydrogen Energy, 46 (42), 22180–22194, DOI: 10.1016/j.ijhydene.2021.04.035.

VILAÇA A.S.I., SIMÃO L., MONTEDO O.R.K., NOVAES DE OLIVEIRA A.P., and RAUPP-PEREIRA F., 2022, *Waste Valorization of Iron Ore Tailings in Brazil: Assessment Metrics from a Circular Economy Perspective*, Resources Policy, Vol. 75 (December 2021), 0–10, DOI: 10.1016/j.resourpol.2021.102477.

WANG Q., ZHANG R., Lv S., and WANG Y., 2021, *Open-Pit Mine Truck Fuel Consumption Pattern and Application Based on Multi-Dimensional Features and XGBoost*, Sustainable Energy Technologies and Assessments, Vol. 43 (July 2020), 100977, DOI: 10.1016/j.seta.2020.100977.

WANG X., DAI Q., BIAN Y., XIE G., XU B., YANG Z., 2023, *Real-time truck dispatching in open-pit mines*, International Journal of Mining, Reclamation and Environment, Vol. 37, pp. 1–20, DOI: 10.1080/17480930.2023.2201120.

YELLISHETTY M., WERNER T.T., and WENG Z., 2021, *Iron Ore in Australia and the World: Resources, Production, Sustainability, and Future Prospects*, [in:] *Iron Ore: Mineralogy, Processing and Environmental Sustainability*, ed. by Liming Lu, Woodhead Publishing: Elsevier, pp. 711–750.

ZHANG L., SHAN W., ZHOU B., and YU B., 2023, *A dynamic dispatching problem for autonomous mine trucks in open-pit mines considering endogenous congestion*, Transportation Research Part C: Emerging Technologies, Vol. 150, p. 104080, DOI: 10.1016/j.trc.2023.104080.