materials proceedings

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Proceeding Paper

Environmental Assessment of Replacing Fossil Fuels with Hydrogen for Motorised Equipment in the Mining Sector †

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† Presented at the 2nd International Conference on Raw Materials and Circular Economy "RawMat2023", Athens, Greece, 28 August–02 September 2023.

Abstract: To achieve the European milestone of climate neutrality by 2050, the decarbonisation of energy-intensive industries is essential. In 2022, global energy-related CO_2 emissions increased by 0.9% or 321 Mt, reaching a peak of over 36.8 Gt. A large amount of these emissions is the result of fossil fuel usage in the motorised equipment used in mining. Heavy diesel vehicles, like excavators, wheel loaders, and dozers, are responsible for an estimated annual CO_2 emissions of 400 Mt of CO_2, accounting for approximately 1.1% of global CO_2 emissions. In addition, exhaust gases of CO_2 and NO_x endanger the personnel's health in all mining operations, especially in underground environments. To tackle these environmental concerns and enhance environmental health, extractive industries are focusing on replacing fossil fuels with alternative fuels of low or zero CO_2 emissions. In mining, the International Council on Mining and Metals has committed to achieving net zero emissions by 2050 or earlier. Of the various alternative fuels, hydrogen (H_2) has seen a considerable rise in popularity in recent years, as H_2 combustion accounts for zero CO_2 emissions due to the lack of carbon in the burning process. When combusted with pure oxygen, it also accounts for zero NO_x formation and near-zero emissions overall. To this end, this study aims to examine the overall environmental performance of H_2-powered motorised equipment compared to conventional fossil fuel-powered equipment through Life Cycle Assessment. The assessment was conducted using the commercial software Sphera LCA for Experts, following the conventionally used framework established by ISO 14040:2006 and 14044:2006/A1:2018 and the International Life Cycle Data Handbook, consisting of (1) the goal and scope definition, (2) the Life Cycle Inventory (LCI) preparation, (3) the Life Cycle Impact Assessment (LCIA) and (4) the interpretation of the results. The results will offer an overview to support decision-makers in the sector.

Keywords: hydrogen; Life Cycle Assessment; decarbonisation; extractive industries

Citation: Peppas, A.; Kottaridis, S.; Politi, C.; Oustadakis, P. Environmental Assessment of Replacing Fossil Fuels with Hydrogen for Motorised Equipment in the Mining Sector. *Mater. Proc.* **2023**, *15*, 5043. https://doi.org/10.3390/materproc2023015043

Academic Editors: Christos Roumpos, Charalampos Vasilatos and Anthimos Xenidis

Published: 10 November 2023

1. Introduction

Global energy-related CO_2 emissions peaked in 2022 at over 36.8 Gt [1]. To achieve Europe's goal of climate neutrality by 2050, minimising these emissions is vital. The decarbonisation of energy-intensive industries is key to this goal, as industrial activities accounted for 9.4 Gt of CO_2 emissions in 2021 [2]. Nearly half of these emissions, 4.5 Gt, were attributed to extractive industries [3]. A significant portion of these emissions is associated with heavy diesel vehicles and motorised equipment used in mining operations, including excavators, wheel loaders, and dozers, producing alone an estimated 400 Mt of CO_2 emissions annually [4]. Another piece of motorised equipment producing significant amounts of emissions is diesel-fuelled generators, which typically cover more than 70% of a mine's electricity demand [5]. In line with the commitment of the International Council on Mining and Metals to achieve net zero emissions by 2050, if not sooner, extractive industries need to take initiatives towards decarbonisation, either with the electrification of equipment or the use of alternative fuels of zero or near-zero CO_2 emissions [6].

Among the different alternative fuels, hydrogen (H_2) has seen a significant rise in popularity in recent years. H_2 combustion generates almost zero CO_2 emissions due to the lack of carbon in the burning process. Furthermore, when combusted with pure oxygen, H_2 accounts for zero NO_x formation, resulting in nearly zero emissions overall. Nevertheless, NO_x formation can be mitigated by keeping the flame temperature below the critical 1350 °C and/or applying catalytic reduction [7]. H_2 has already seen application in motorised equipment and vehicles utilising internal combustion engines (ICE), such as H_2 gensets and backhoes, resulting in negligible emissions of CO_2 and only small amounts of water vapours [8,9]. H_2-fuelled ICEs are particularly advantageous for heavy motorised equipment, where other decarbonisation approaches, such as electrification, are not a viable option [10]. The electrification of excavators, for example, would require a very large battery pack, which would significantly increase the costs of operation. The high energy density of compressed H_2 allows the operation of the equipment with acceptable-sized tanks. In addition, the existing ICEs can be turned into H_2-fuelled with only slight modifications, which significantly decreases retrofitting costs [11].

The scope of this study is to analyse the environmental performance of replacing fossil fuels with H_2 in the motorised equipment used in mining through Life Cycle Assessment (LCA). The analysis considered iron ore mining using diesel-fuelled equipment as the case study, developing cradle-to-gate models for energy/fuel production and consumption. The partial Life Cycle Impact Assessment (LCIA) conducted examined the environmental indicators of Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Formation (POF), which were selected to address the overall emissions from H_2 combustion, including NO_x, and the effectiveness of mitigation approaches. The results of the analysis will provide decision-makers in the mining sector with valuable insights to implement sustainable strategies and support the transition towards greener and more efficient practices for the sector.

2. Materials and Methods

2.1. LCA Methodology

To assess the environmental impact of replacing fossil fuels with H_2 for motorized equipment in the mining sector, an LCA was performed by the procedures described by ISO 14040:2006 and 14044:2006/A1:2018 and the International Life Cycle Data Handbook [12–14]. The framework consists of (1) the goal and scope definition, (2) the Life Cycle Inventory (LCI) preparation, (3) the Life Cycle Impact Assessment (LCIA), and (4) the result's interpretation.

The LCA was conducted using the commercial software package Sphera LCA for Experts (FE), Chicago, United States [15]. The software allows for constructing and simulating value chains consisting of multiple processes. The databases of the software provide models for processes, considering all inputs and outputs from data drawn from real industrial processes. Utilising these data, the software then calculates the impact of the designed processes, expressed in relative impact categories, such as GWP.

2.2. Goal, Scope and Functional Unit

The goal is to assess the environmental performance of H_2-fuelled motorised equipment compared to diesel-fuelled in the iron mining sector through a cradle-to-gate LCA. The study considered the production and combustion of diesel and H_2 and was extended to include all electricity production and consumption, presenting the overall impact of the two scenarios. The functional unit was 1 tonne of iron ore produced.

2.3. Life Cycle Impact Assessment

LCIA quantifies the environmental impact using the results of the analysis and the impact factors. In this particular study, four impact categories at the midpoint level were selected to present the possible environmental benefits, including GHG reduction, as well as possible drawbacks, such as Photochemical Ozone Formation, of H_2 exploitation, for a more accurate assessment. The impact categories selected are presented in Table 1.

Table 1. LCIA impact categories.

Impact Category	Selected Indicator	Unit
Climate Change	Global Warming Potential (GWP) (CML 2016)	kg CO_2 eq.
Acidification	Acidification Potential (AP) (CML 2026)	kg SO_2 eq.
Eutrophication	Eutrophication Potential (EP) (CML 2016)	kg Phosphate eq.
Photochemical Ozone Formation	Photochemical Oxidant Formation (POF) (ReCiPe 2016)	kg NO_x eq.

2.4. Life Cycle Inventory

LCI comprises all inputs and outputs data of the examined system, including materials, energy, emissions, etc. To ensure data credibility, Sphera LCA for Experts databases were utilised as much as possible. Data for processes not included in the databases were drawn from the literature.

Energy consumption for drilling and blasting, crushing and screening, and stacking and reclaiming were drawn from [16]. For scenario 1, data for diesel-fuelled excavators, trucks, and gensets and the production of necessary diesel for all processes were drawn from Sphera LCA for Experts databases. The electrical grid was simulated as the average EU-28 country grid mix, 1–60 kV, drawn by the Sphera LCA for Experts databases. For scenario 2, data for the H_2 ICEs of the equipment were drawn by [17]. H_2 consumption was estimated considering the equipment's energy requirements and the energy density of H_2 [18]. For the mining of 1 tonne of iron ore, 0.343 kg of H_2 was consumed. The required H_2 was produced by water electrolysis utilising electricity from photovoltaics; the data for both processes were drawn from Sphera LCA FE databases. The required electricity for H_2 production was 65.79 MJ.

2.5. Scenario Description

Overall, two scenarios were planned. Scenario 1 was designed to serve as the base case, simulating the use of diesel-fuelled motorised equipment [16]. Mining starts with the drilling and blasting processes followed by the excavation of unprocessed ore and its loading on haul trucks, transporting it to the crushing, screening, and separation facilities, where beneficiation, classification, and grading of the ore occurs. The ore is then stacked and stockpiled, ready to be loaded on trucks or rail containers to be transported out of the mine. Diesel required for drilling equipment, excavators, and trucks is produced in refineries. Electricity required for crushing, screening, stacking, and reclaiming is provided by 70% from diesel-fuelled gensets and 30% by the electrical grid [5].

Scenario 2 was designed to simulate the use of H_2-fuelled motorized equipment. Specifically, drills, excavators, trucks, and gensets were replaced with H_2 fuelled-ones. H_2 was considered to be produced by water electrolysis, utilising electricity from photovoltaics (PVs), and distributed to the H_2-fuelled equipment. As in scenario 1, gensets covered 70% of the electricity demand of the mine. The system boundaries of the two scenarios are shown in Figure 1.

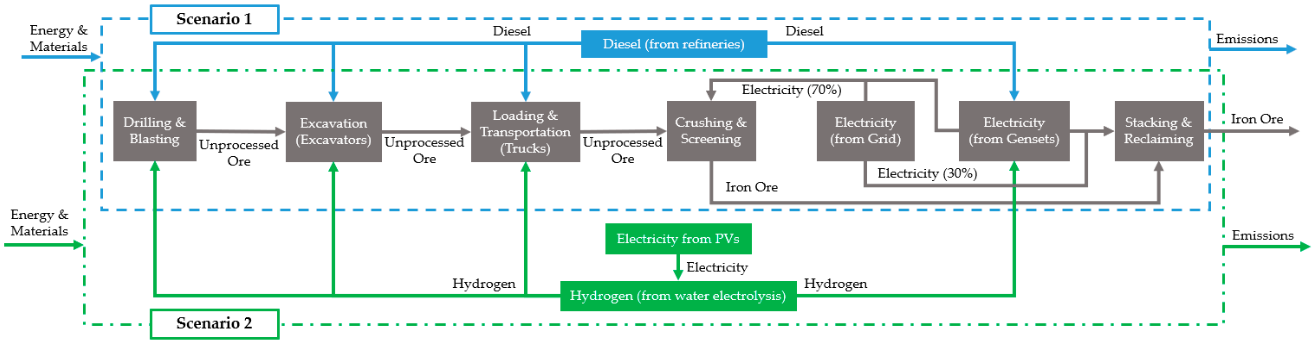

Figure 1. Scenarios' system boundaries.

3. Results

Figure 2 summarises the results of the analysis. H_2 utilisation results in significant reductions for all impact categories. The carbon-absent combustion of H_2 resulted in an overall 77.22% reduction in GWP: 0.87 kg CO_2 eq. compared to 3.82 kg CO_2 eq. AP was also reduced by 77.61%: from 0.0147 kg SO_2 eq. to 3.29×10^{-3} kg SO_2 eq. EP was reduced from 2.88×10^{-3} kg Phosphate eq. to 2.94×10^{-4} kg Phosphate eq., which is a reduction of 89.79%. Considering POF, the utilisation of green electricity for H_2 production and optimal H_2 combustion techniques keep NO_x formation, the main emission produced from H_2 combustion, to a minimum. Thus, POF actually presents the most significant reduction, 91.49%, dropping from 0.0208 kg NO_x eq. to 1.77×10^{-3} kg NO_x eq. Therefore, the majority of emissions related to green H_2, are attributed to the electricity production process, specifically from infrastructure construction and operation, as electricity is generated from RES.

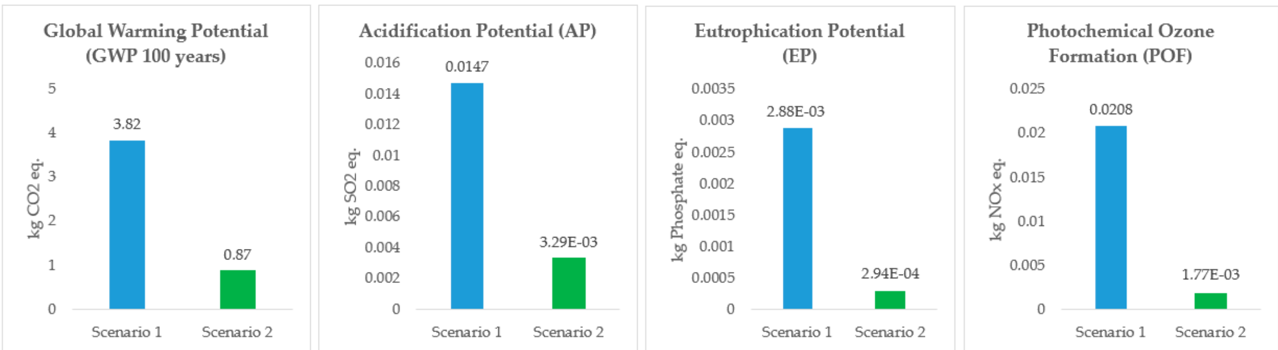

Figure 2. LCIA results for both scenarios.

4. Discussion

The results demonstrate the environmental advantages of utilising H_2 for motorised equipment compared to conventional fossil fuels in the mining sector. Nevertheless, the large-scale utilisation of H_2 in motorised equipment in the mining sector, or energy-intensive industries in general, faces various challenges. A serious challenge is in regard to the H_2 production method, with non-RES, highly emissive sources such as coal (brown H_2) being even more impactful than conventional fossil fuels. According to the literature, grey, blue, and yellow H_2 account for approximately 16, 13, and 14.5 kg CO_2 eq. per kg produced, respectively, while green H_2 accounts for less than 2 kg CO_2 eq. per kg [19]. However, green H_2 can be one of the costliest approaches, ranging from 2.2 to 8.2 €/kg, due to the high electricity demand. Grey and blue H_2, on the other hand, range from 0.8 to 2.1 €/kg and 1.2 to 3 €/kg [19]. Therefore, while production from RES electricity (green H_2) is one of the most environmentally beneficial solutions, the significant RES electricity demands raise the challenge of both increasing RES penetration and availability while also reducing production costs.

Furthermore, H_2's overall handling also poses challenges. On the one hand, as a highly flammable substance, H_2 requires intricate production, storage, and distribution equipment coupled with extensive safety systems. On the other hand, as H_2 utilisation is a relatively new approach, regulations, procedures and overall technical guidelines considering safe handling are still developing and are on occasion difficult to acquire for practitioners or researchers.

Despite all these, the role of H_2 in the EU goals for climate neutrality is universally acknowledged, and therefore, various consumption or production plants have been developed or are under development. In 2009, a 12 MW H_2-fueled power plant was commissioned in Italy, using a combined-cycle gas turbine and reformed H_2 with an estimated production of 60 million kWh a year [20]. In 2023, the construction of the biggest green H_2 production plant in the world began in China, accounting for a total of 720 MW RES capacity and 288,000 m^3 H_2 storage capacity [21]. These projects are strongly linked and supported by the rapid expansion of RES electricity production across the globe.

It is therefore evident that large-scale exploitation is on the way and can arrive even sooner through the collaboration of governments, energy-intensive industries, technology providers, and researchers. Policy support, strong regulatory frameworks, and financial incentives can facilitate the transition towards H_2-based solutions and overall environmental and economic sustainability.

5. Conclusions

Replacing fossil fuels with cleaner energy sources in the motorised equipment of energy-intensive industries, such as mining, is integral for their overall decarbonisation. H_2 utilisation is one of the most viable solutions towards this goal, especially for energy-intensive industries. To this end, this study aimed to assess and quantify said benefits, comparing H_2 with the conventionally used diesel for the motorized equipment of the mining sector, specifically iron ore mining, through LCA.

The analysis showed the following results by replacing fossil fuels with green H_2:

- GWP was reduced by 77.22%.
- AP was reduced by 77.62%.
- EP was reduced by 89.79%.
- POF was reduced by 91.49%.

Despite being the indicator addressing NO_x emissions, indicating that when proper combustion techniques are applied, NO_x formation can be almost non-existent.

In conclusion, as more and more studies suggest its numerous environmental benefits, the large-scale utilisation of green H_2 presents one of the most viable solutions for achieving the EU's and the world's sustainability goals. In this scope, further research for the optimisation of H_2 production and combustion technologies and detailed techno-economic analyses are the next step towards expanding H_2 utilisation, making it a powerful asset in achieving the 2050 climate neutrality goals.

Author Contributions: Conceptualisation, A.P.; methodology, A.P., C.P. and S.K.; validation, A.P., C.P. and P.O.; investigation, S.K.; writing—original draft preparation, S.K.; writing—review and editing, C.P.; visualisation, S.K.; supervision, A.P. and C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data sources used are cited and all data produced are reported in the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IEA. CO_2 Emissions in 2022, IEA, Paris. License: CC BY 4.0. 2023. Available online: https://www.iea.org/reports/co2-emissions-in-2022 (accessed on 26 June 2023).
2. IEA. Industry, IEA, Paris. License: CC BY 4.0. 2022. Available online: https://www.iea.org/reports/industry (accessed on 26 June 2023).
3. Fedorov, E. Metals & Mining Decarbonisation and Sector Disclosure. Available online: https://think.ing.com/articles/metals-mining-decarbonisation-sector-disclosure (accessed on 26 June 2023).
4. Nordstrand, M. Electrifying Mining Operations. Available online: https://www.globalminingreview.com/special-reports/01102022/electrifying-mining-operations/ (accessed on 29 June 2023).
5. Why the Mining Industry Relies on Diesel Engine Generators. Available online: https://www.reactpower.com/blog/why-the-mining-industry-relies-on-diesel-generators/ (accessed on 4 July 2023).
6. ICMM CLIMATE CHANGE STATEMENT. Our Commitment to a Goal of Net Zero by 2050 or Sooner. Available online: https://www.icmm.com/website/publications/pdfs/mining-principles/net-zero-by-2050_en-gb.pdf (accessed on 6 June 2023).
7. Menzies, M. Hydrogen: The Burning Question. Available online: https://www.thechemicalengineer.com/features/hydrogen-the-burning-question/ (accessed on 29 June 2023).
8. Jackson, T. Future Fuels Pt. 4: Hydrogen Propulsion Technologies on the Rise. Available online: https://www.equipmentworld.com/alternative-power/hydrogen-fuel-cell/article/15303686/hydrogen-propulsion-technologies-for-construction-equipment (accessed on 29 June 2023).
9. A Guide to Hydrogen Generators (Gensets). Available online: https://www.hydrologiq.com/a-guide-to-hydrogen-generators-gensets/ (accessed on 5 July 2023).
10. Nebergall, J. Examples of Hydrogen Engines in Mobility and Transportation. Available online: https://www.cummins.com/news/2022/01/27/examples-hydrogen-engines-mobility-and-transportation (accessed on 29 June 2023).
11. What Is a Hydrogen Engine? A Comprehensive Guide to Hydrogen-Powered Technology. Available online: https://www.lhyfe-heroes.com/about-hydrogen/what-is-a-hydrogen-engine-a-comprehensive-guide-to-hydrogen-powered-technology (accessed on 26 June 2023).
12. ISO 14040:2006. Environmental Management—Life Cycle Assessmen—Principles and Framework. Available online: https://www.iso.org/standard/37456.html (accessed on 9 June 2023).
13. ISO 14044:2006. Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Available online: https://www.iso.org/standard/38498.html (accessed on 9 June 2023).
14. European Platform on Life Cycle Assessment. Available online: https://eplca.jrc.ec.europa.eu/ (accessed on 9 June 2023).
15. Sphera. LCA for Experts (GaBi). Available online: https://sphera.com/life-cycle-assessment-lca-software/ (accessed on 29 June 2023).
16. Haque, N.; Norgate, T. 20—Life cycle assessment of iron ore mining and processing. In *Iron Ore*; Lu, L., Ed.; Woodhead Publishing: Sawston, UK, 2015; pp. 615–630.
17. Candelaresi, D.; Valente, A.; Iribarren, D.; Dufour, J.; Spazzafumo, G. Comparative life cycle assessment of hydrogen-fuelled passenger cars. *Int. J. Hydrogen Energy* **2021**, *46*, 35961–35973. [CrossRef]
18. Energy Density of Hydrogen. Available online: https://hypertextbook.com/facts/2005/MichelleFung.shtml (accessed on 4 July 2023).
19. Ajanovic, A.; Sayer, M.; Haas, R. The economics and the environmental benignity of different colours of hydrogen. *Int. J. Hydrogen Energy* **2022**, *47*, 24136–24154. [CrossRef]
20. Enel's Fusina Hydrogen-Fueled Plant Goes Online. Available online: https://www.powermag.com/enels-fusina-hydrogen-fueled-plant-goes-online/ (accessed on 15 June 2023).
21. World's Largest Green Hydrogen Plant Starts Construction. Available online: https://www.tankstoragemag.com/2023/02/20/worlds-largest-green-hydrogen-plant-starts-construction/ (accessed on 13 June 2023).