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Viability analysis of underground mining machinery using green hydrogen as a fuel

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HIGHLIGHTS

- Diesel combustion in underground mining produces a great quantity of pollutants.
- Mining sector is willing to apply technologies like hydrogen to solve health issues.
- Viability study for green hydrogen as a fuel for underground mining was performed.
- NPV of € 12,051,391 and a 7.78-year pay-back were obtained.
- The emission of up to 16,537 tonnes of CO_2 per year can be prevented.

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ABSTRACT

The processes and logistics of the mining industry have continually undergone transformations in order to deal with rigorous regulations, economic considerations, safety and the social burden regarding environmental conditions (i.e. every sustainability pillar). In underground mines, the use of diesel-powered machinery has been increased in the past decades. The combustion of diesel fuel produces a great quantity of pollutants (i.e. gas emissions, particulate matter, etc.). Thus, a constant ventilation is required to satisfy the regulations on health and safety of miners. One of the innovative transformations that underground mining processes have adopted is the use of electrical Load Haul Dumps (LHDs) to reduce the in-mine emissions and the ventilation burden and to improve in-mine working conditions, among other benefits. Electric mobile LHDs could be further improved by replacing battery-based energy supplies with hydrogen fuel cells. The present work focuses on the techno-economic assessment of modifying electrical LHDs by incorporating different processes and equipment (i.e. fuel cell stacks, storage tanks, DC/DC converters). The base case considers the modification of the whole mining fleet of diesel-based LHDs.

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As a result, a positive Net Present Value (for the project time span under consideration) and a payback period of 7.78 years were observed. The sensitivity analysis showed that considerable modifications of the current states of diesel price are required so that modifications are not feasible (diesel prices of 0.53 €/l). A tight electricity cost of 70 €/MWh was obtained as a breaking point (considerably safe for several industrial conditions).

Introduction

Hydrogen fuel cells are a well-known, broadly applied power technology. Chosen for their reliability, safety and high power density, fuel cells have provided electric power to vehicles (space missions, city buses, submarines, locomotives) and power plant applications (home and network). In fact, all major automakers have advanced fuel cell projects (e.g.: Toyota has doubled the investment in hydrogen fuel cell vehicles and developed the Toyota Mirari [1,2]; Hyundai has recently showcased the Nexo model (2018)). Hydrogen fuel cells will allow energy security and environmental benefits [3,4], since the use of fossil fuels in internal combustion engines is one of the keys of air pollution and climate change. The use of Proton Exchange Membrane Fuel Cell (PEMFC) devices could replace the current internal combustion engines. This technology would be used in the transport sector and in other different industrial applications [5,6]. However, it is necessary to create specific policies and regulations that allow the development of Fuel Cell Electric Vehicles in order to develop the hydrogen economy. For example, it is necessary to build an infrastructure to refuel vehicles, including buses, trucks, duty vehicles, etc., so that the market of FCEVs can be developed [7]. Different economic evaluations shown that the Net Present Value (NPV) of hydrogen projects is positive and commercially viable and attractive [8], but currently the widespread growth of hydrogen use is limited by the small number of stakeholders, the consumer perception, the lack of hydrogen infrastructure, the hydrogen safety and the scarce policies and regulations that establish more favourable conditions to sustain the development of the hydrogen economy [9].

The mining industry is willing to apply new technologies to solve health and safety, productivity and operational efficiency issues. Currently, the mining industry is motivated to consider alternative power systems for those conventional diesel combustion engines that are part of the mining machinery [10].

The quality of underground mine air must be controlled, particularly in light of the stricter regulatory standards concerning diesel particulate matter (PM). The intensive use of diesel-powered machinery produces gas emissions and particulate pollutants due to fuel combustion. Thus, underground mines require a continuous airflow to comply with health and safety regulations [11]. The acknowledgement that PM is a carcinogenic [12] concerns all industry stakeholders. Nevertheless, metal mines are now highly mechanized and predominantly use diesel during the primary handling of ore. Fuel cells produce no harmful emissions and only generate electricity and water, therefore offering a viable alternative to improve the underground work environment. However, there is very little motivation for the major engine suppliers of the mining industry to dramatically improve their engine technology given the relatively small market that underground mining represents. Thus, the current alternatives to make diesel power cleaner are limited to exhaust filters and cleaner diesel fuel (in some cases, electrical power plant systems with voluminous trailing cable are used). None of these options meet all the existing regulations on diesel emissions and on the impact of the heat generated by diesel engines on the underground work environment [13].

Before the underground mining industry can apply fuel cells in their machinery, a range of operational aspects which may include health and safety risks, regulatory issues, system fitness with mining processes, technical risks and operating and capital costs must be considered. Mining companies have shown on numerous occasions that they are willing to support the development of alternative energy systems once all risks have been reduced to acceptable levels (e.g. a fuel cell locomotive in Anglo American Platinum [14]).

Underground mining is one of the most promising applications for fuel cell-powered machines because the new technology may be able to compete strictly on economic merits (e.g. Ref. [14]). The mining industry is highly regulated, thus representing a challenging integration field for new technologies. The underground mining industry also have economic incentives associated with the adoption of a low or zero-emission power source. Conventional underground mining power technologies include wired electrical, diesel and battery-powered machinery. While each of these technologies have their own niche market, they are not necessarily clean or safe in a wide range of underground operations. Mature hybrid fuel cell-powered equipment for underground mining may have the potential to offer these benefits in an economically viable package.

The underground mine operators have several drivers that favour low or zero-emission vehicles (e.g. fuel cell-hybrid Load Haul Dumps (LHDs) [15]). For example, air must continually be pumped into the mine to provide fresh air for human consumption and oxygen for fuel combustion in internal combustion (IC) engines and to clear the working area of airborne particles and fumes [11]. In some cases, the amount of ventilation required for a particular mining operation is determined by the amount of diesel IC engines running in that area. In those cases, it is possible to reduce the mine ventilation requirements by replacing diesel IC engines with fuel cell-powered equipment. Besides reducing ventilation costs, the sound generated by the peripheral power plant sub-systems supporting fuel cells is expected to be less than their diesel engine counterparts.

Obviously, the underground mining industry will continue to use the available technologies that allow the completion of their mission with the minimum infrastructure and workforce and at the lowest capital equipment cost. Thus, if an efficient, regulation-compliant, cost-competitive fuel cell machine which would satisfy the mine requirements could be designed and built, it would have an excellent chance of being widely adopted by the mining industry.

Mining companies are facing significant challenges in their efforts to decarbonise; therefore, they are looking for more opportunities to incorporate dynamic technologies in order to support those efforts. In many cases, the challenge is to do it without limiting the efficiency of the extraction and processing systems. Renewable energy solutions can respond to many of those challenges; however, some companies need an alternative dynamic solution. As an emission-free fuel that has been used in new mining processing applications, heavy-duty vehicles and electricity generation, hydrogen has the flexibility to deal with some of the processing and operational challenges that the mining sector is currently facing. In mining operation, the use of hydrogen and fuel cell technologies is possible; nevertheless, the hydrogen distribution and storage will be analysed. For example, the literature report that the potential use of salts to store hydrogen in underground mines [16]. The conditions of the operation mine could determine how the hydrogen would be stored (technical and economic conditions).

Based on the aforementioned information, the present work focuses on a viability analysis (techno-economic assessment) of the implementation of hydrogen fuel cells as a primary energy supply in mobile mining machinery. The evaluation would consider the implementation of different components in order to extend the vehicles autonomy to fuel cell-powered LHDs (hydrogen tanks, polymeric fuel cells and DC/DC converters). In order to do so, the LHD fleet would be considered to be fully replaced (LHDs acquired and modified according to the descriptions detailed in the methodological section).

By incorporating extended hydrogen-based electrical systems, the vehicle autonomy may be increased as charging processes might be considerably lower than battery recharging [17] (e.g. a hydrogen tank with a 30-kilo capacity can be charged in about 8 minutes at 350 bars, which can deliver about 520 kWh after passing the stack; considering an energetic density of 0.60 kWh/kg, this is superior to a normal battery energy supply ~0.15 kWh/kg).

Methods

General description of fuel cell electric vehicles

A progressive decarbonisation process of the transport sector that is based on the improvements in fuel efficiency and on the reduction of fuel carbon intensity will not be possible if it is only justified by a technological background. Policies that promote significant changes in industry and society are required to accelerate the implantation of alternative-fuel vehicle technologies (e.g. battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and extended-range electric vehicles (EREV)) [7]. Despite adopting these alternatives, lower carbon fuels and powertrains are only a beginning, as these well-known non-polluting vehicle technologies cannot be the sole solution to the problems of carbon emissions [3,5]. The electricity that they use does not pollute the workplace; however, it typically pollutes the environment during its production as it is primarily generated from carbon-emitting coal-fired power plants [11]. Evidently, there are other zero-emission alternatives, such as Fuel Cell Electric Vehicles (FCEV) or hydrogen vehicles; these are attractive alternatives to fossil fuels, especially if hydrogen is produced from renewable sources (hydraulic, wind, solar, biomass, geothermal) [12]. The fuel cells themselves have lately undergone dramatic improvements in efficiency and cost, but the infrastructure needed to support them continues to be a weakness.

Low-temperature Polymer Electrolyte Membrane (PEM) fuel cells are currently used for automotive applications almost exclusively. In the PEM fuel cell, hydrogen is made into water by reacting with oxygen. This technology has a high degree of maturity and is characterised by a simple setup, a fast response to load changes, good cold start properties and a high-power density [18].

Fuel cell stacks are formed by several hundred cells which are built into a vehicle powertrain, thereby power outputs of 100 or more kW can be achieved. The catalytic coating of electrodes with platinum materials is an expensive feature of PEM fuel cells. In order to lower the costs, the aim of fuel cell production is to reduce the platinum content without adversely affecting the function of the fuel cell.

The fuel cell system also needs a wide range of control systems to operate, including a hydrogen air management system to supply the fuel cell stack, a thermal management system (particularly for cooling the stack) and a system to manage the electric drive and the electrical system of the vehicle. All of these auxiliary consumers require several kilowatts of parasitic power and thus have a detrimental effect on the system efficiency [19].

Fuel cells have further benefits; for example, heat can be drawn from the fuel cell stack's coolant circuit, thereby avoiding power losses for auxiliary air heaters (about 5 kW in comparison with battery electric vehicles [20]). Regardless of this benefit, the PEM fuel cell operating temperature of 80–85 °C cannot be exceeded significantly, so additional electrical power for cooling the stack is needed. Moreover, operations in extremely hot regions represent a technical challenge [18].

Besides the fuel cell stack, a fuel cell vehicle also has a traction battery (usually lithium-ion or nickel-metal hydride rechargeable batteries). The electrical power of the fuel cell or the powertrain regenerative operation (recovery) can be temporarily stored in this battery, which also serves to cover short-term power peaks and is operated at a much higher voltage than the current vehicle electrical system (12 V).

The electric powertrain of fuel cell electric vehicles, i.e. electric engines and power electronics, is no different from the drive of battery electric vehicles. If the fuel cell stacks supply electrical power directly to the electric engine, it is described as a fuel cell-dominant system. If the fuel cell stack only supplies the traction battery (which, in turn, is the sole power supply of the electric motor), this type of vehicle is known as a battery electric vehicle with range extender.

Case of study

The description of the base case is founded on a general underground mine that needs to modify a fleet of 40 LDHs. These LHDs are considered to be diesel-powered and will be replaced by electric vehicles with extended autonomy through hydrogen. In order to extend the autonomy of these electric vehicles through hydrogen, the main components of the range extension are considered to be hydrogen storage tanks, polymer fuel cells and DC/DC converters. The fleet is considered to operate 300 days per year and 24 hours per day.

The description of the vehicles under consideration and the hydrogen production plant are described in the next subsections.

Vehicle description

The electric components of the vehicles have the following specifications:

- Traction drive: Artisan 1200 Series traction motor - 630 VAC/108 kW, 149 kW peak single power inverter.
- Hydraulic drive: Artisan 200 Series auxiliary motor - 630 VAC/76 kW, 113 kW peak single power inverter.
- Battery drive: Artisan, 165 kWh, LiFePO4, 630 VDC. Only 85 kWh of battery drive are needed in the base electric vehicle because the hybridisation with fuel cell systems will suffice.
- Battery charger: Artisan 65 kW Master Service, input 575VAC.

To achieve the extended autonomy through hydrogen, the following components are considered:

- Ballard's 60 kW peak power polymer fuel cell.
- 4 hydrogen tanks type III at 350 bars mounted on a rack, with a total capacity of 30 kilograms of hydrogen from the manufacturer Worthington.
- DC/DC converter, so that the fuel cell works directly with the batteries of the LDH and the electric low-profile trucks of the manufacturer Farnell.

With the implementation of extended hydrogen autonomy, the amount of power stored increases from 165 kWh of the initial batteries to 605 kWh (30 kilograms of stored hydrogen ~33.33 kWh/kg x 30 kg H_2 x 0.52 fuel cell efficiency). Setting the electric vehicle with extended autonomy, the fuel cell will be the main propulsion system. The point of maximum efficiency of the fuel cell will be considered to be between 40 and 70% of charge. The batteries will absorb the transients originated by accelerations and braking. Fig. 1 is a schematic of the different LHD components considered in the present work and their interaction.

The extra cost that a conventional diesel-powered mining vehicle would have in comparison with the same electric vehicles after the implementation of the extended hydrogen autonomy would be as of 300,000 €/unit (i.e. € 12,000,000 for the whole fleet). The maintenance costs are considered to be the same as those of the conventional vehicles being replaced, although these has been proven to be noticeably lower since there are no moving parts and there is electric traction [21].

Hydrogen production plant description

It is considered that mining vehicles have a consumption of about 20 l/h of diesel or 2.66 kg of hydrogen/h (1 kg of hydrogen is equivalent to 7.5 l of diesel, because it has 3.3 times more power and the efficiency of the fuel cell is more than double). The consumption of each of the machines is 480 l/day in the case of diesel or 64 kg/day in the case of hydrogen (i.e., a hydrogen plant capable of supplying 2560 kg/day must be built).

The main processes that are part of the whole centralized hydrogen production plant and the Hydrogen Refuelling Station (see Fig. 2) are based on current technologies which have been quoted in order to obtain a base scenario for the techno-economic analysis. The main technology used to produce hydrogen is associated with water electrolysis [22–24] and the green hydrogen is obtained from the use of renewable energy sources. Other technologies, such as biomass gasification, steam reforming, pyrolysis, etc., have also been used to develop the hydrogen energy vector [25–32]. In this case, water electrolysis will be implemented.

The description of these processes is as follows:

- **Alkaline electrolyser**: This equipment is scaled for a total consumption of 6.6 MW of electricity, which comes from the stack (consumption of 6 MW) and the accessories, the control and other components considered in the total plant balance (the remaining 0.6 MW). The whole process is considered to be supplied with renewable energies. The scaled electrolyser consumes 15 l of untreated water per kg of produced hydrogen. The process production is in the order of 2560 kg of hydrogen per day and 21,311 kg of oxygen per day (hydrogen at 30 bars of pressure and a purity of 99.999% and oxygen at 5 bars of pressure and a purity of 99.95%, respectively) or 106.6 kg of hydrogen per hour and 888 kg of oxygen per hour. In addition, there would exist a surplus of thermal energy (72 MWh per day or 3 MWh per hour) when using water, with an exit temperature of 65 °C and an incoming temperature of 50 °C. Although the oxygen and the remaining heat could be considered as by-products of the electrolysis process, they would not be considered for the present evaluation (i.e., the use of these by-products could improve the economic results).
- **Low pressure hydrogen storage**: The hydrogen obtained by the electrolysis process would be stored at the production pressure (30 bars in a low-pressure hydrogen vessel). The generated hydrogen would be stored at the generation pressure in order to reduce the CAPEX of the storage system and to simplify the installation, as the space is considered to be enough to install the necessary hydrogen tanks. It is considered necessary for the storage to have a capacity equivalent to 48 hours of full load operation of the alkaline electrolyser (5120 kg of hydrogen), which would allow some flexibility and margin to uncouple the hydrogen generation and the supply of the aforementioned hydrogen to the final consumers. The storage system will consist of 13 tanks

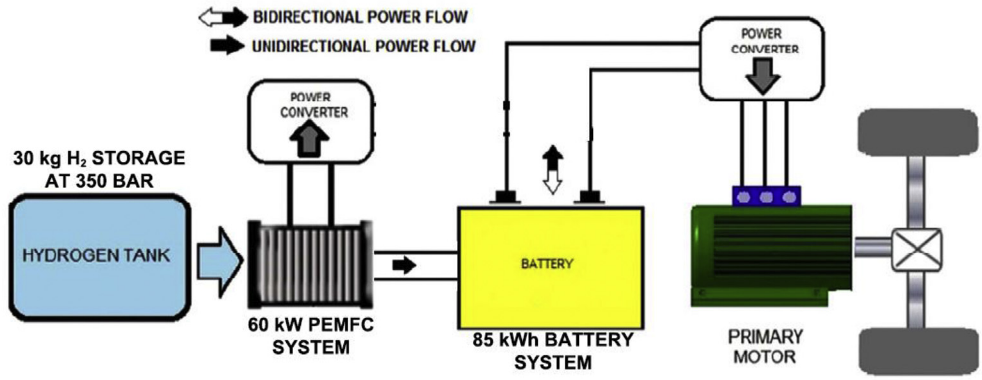

Fig. 1 – Schematic of an electric vehicle with hydrogen range extender.

with a capacity of 150 m^3 of an equivalent volume of water at 30 bars of pressure, which can store about 400 kg of hydrogen per tank. All these tanks will be interlinked to the same inlet manifold and the same outlet manifold, so that they can be managed as a single storage.

- **Hydrogen Compressor**: In order to supply hydrogen to the high-pressure storage, it is necessary to compress the hydrogen, so a compressor is necessary as well. A membrane compressor has been selected for this case, given that they are the most suitable ones to work with high purity hydrogen. The compressor will have the capacity to compress up to 1500 Nm^3/h of hydrogen from 5-bar pressure (to use the maximum hydrogen storage capacity) to 350 and 525-bar pressure in order to create a cascade and save energy during the hydrogen compression and storage. It is necessary to consume up to 350 kWh of renewable energy to carry out this work, which would generate up to 280 kWh of residual thermal energy with an outlet temperature of 65 °C and an inlet temperature of 50 °C. This residual heat can be used for different applications; nonetheless, the use of the residual heat has not been considered in the present study.
- **High-pressure hydrogen storage**: The hydrogen from the low-pressure vessel passes through the hydrogen compressor in order to increase the pressure and then it is stored at a high storage pressure (in this case, at 350-bar vessels and at 525-bar vessels). It is considered necessary to have 1500 kg of hydrogen at 350 bars of pressure and 800 kg of hydrogen at 525 bars. This cascade implies more vessels, thus more area is needed; on the other hand, the efficiency is greater and the use of electricity in the compression stage is lower. Given the hydrogen storage at high pressure and the compressor working with hydrogen from the low-pressure hydrogen storage, it is possible to smoothly supply hydrogen for LHDs and other machinery used in underground mines. The system of 1500 kg of hydrogen stored at 350 bars would consist of 38 tanks with a capacity of 1650 l of an equivalent volume of water or 39.5 kg of hydrogen per tank. All these tanks would be interlinked to the same inlet manifold and the same outlet manifold, so that they can be managed as a single storage. The system of 800 kg of hydrogen stored at 350 bars would consist of 83 tanks with a capacity of 300 l of an equivalent volume of water or 9.7 kg of hydrogen per tank. All these tanks will be interlinked to the same inlet manifold and the same outlet manifold, so that they can be managed as a single storage.
- **Hydrogen dispenser**: The international standard ISO 17268:2012 (as well as SAE J2600) defines the connection device for the refuelling of hydrogen land vehicles. It applies to different working pressures and includes the

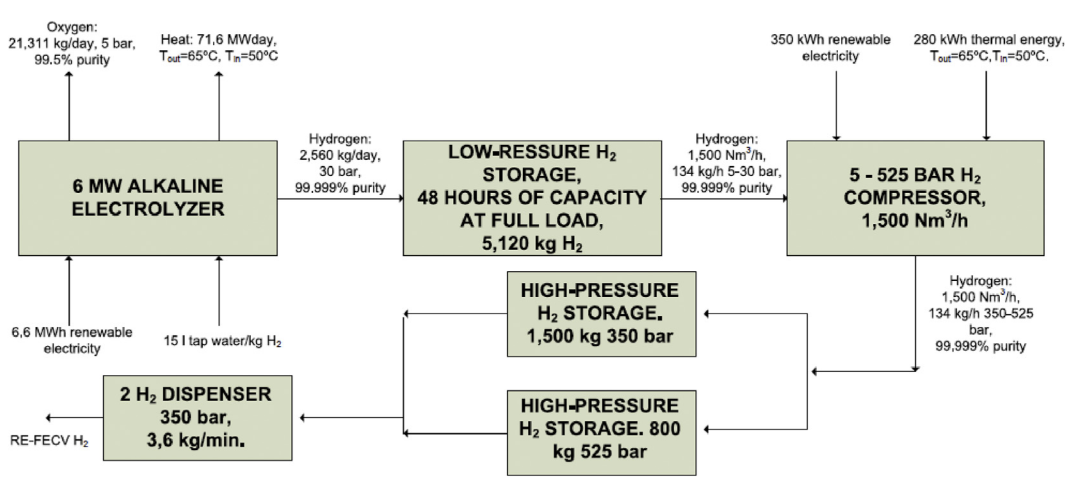

Fig. 2 – Schematic of the hydrogen production plant and the hydrogen refuelling station.

high-flow refuelling of commercial vehicles at 350 bars. Besides the dispensing connector, the refuelling process is also standardised. SAE J2601 addresses the refuelling of light duty vehicles, SAE J2601-2 refers to heavy duty vehicles and SAE J2601-3 regulates fork lifts. SAE J2601-2 recommends SAE J2799 as the communication protocol. It makes a difference between slow, normal and fast-fuelling, the latter being limited to 120 g/s (7.2 kg/min). We will use two hydrogen dispensers with two nozzles each in order to refill LHDs and low-profile trucks at 350 bars with a maximum flow rate about 60 g/s or 3.6 kg/min. We use type III vessels in vehicles and a supply pressure of 350 bars. This setting allows to avoid the use of a hydrogen chiller, which is interesting as regards saving money when the use of a chiller in the hydrogen refuelling station is not possible.

Finally, the hydrogen production plant and the hydrogen refuelling station would be located in the underground mining facilities (just close to the main entrance of the underground mine, but outside it). A PPA (Power Purchase Agreement) would be subscribed for all the electricity consumption (mainly done by the electrolyser and the hydrogen compressor); this contract would include a warranty of origin, which means that all the electricity supply within the scope of this PPA would come from renewable energies like PV, wind, hydraulic and geothermal.

Costs and sensitivity analysis

The economic analysis is mainly based on the capital costs (CAPEX). Operational costs (OPEX), contingencies and other component costs have been obtained from the estimated CAPEX. The capital costs include the main equipment for the hydrogen range extenders (such as PEM fuel cells, hydrogen storage at 350 bars and DC/DC converters) and the main equipment for the hydrogen production plant and the hydrogen refuelling station (such as the hydrogen production electrolysis system, the low-pressure hydrogen storage, the hydrogen compressor, the high-pressure hydrogen storage and the hydrogen dispensers).

For the hydrogen range extender system, the hydrogen production plant and the hydrogen refuelling stations, complementary equipment (such as civil works and mechanical, gaseous, electrical and control integration systems) would be considered. The operational costs would include water, electricity, maintenance, personnel and property leasing costs. The evaluation of the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Payback Period (PB) has been done according to the project evaluation methods [33–35]. The main European manufacturers' amounts have been considered in the estimation of the main equipment costs. An 8% internal rate and a temporary horizon of 25 years were used in the economic assessment.

Furthermore, sensitivity analyses were performed to assess some of the most important parameters, such as the electricity price and the fossil fuel prices. These two parameters are the only ones that will change in the future because we have been working with a specific captive fleet in a specific mine with a specific hydrogen consumption and specific investment costs and operation hours.

Considerations for the techno-economic study

The following factors have been taken into consideration when outlining the techno-economic study:

The CAPEX and OPEX of the hydrogen production facility and hydrogen refuelling station are:

- 6 MW alkaline electrolyser. CAPEX about 750 €/kW and OPEX about 1.5% of investment costs per year. Stack replacement: 80,000 hours or 10 years with a cost about 30% of the investment costs.
- 5120 kg of hydrogen stored at 30 bars of pressure. CAPEX about 220 €/kg and OPEX about 1% of investment costs per year.
- 1200 Nm^3/h of flow rate for a hydrogen compressor with a suction pressure about 5 bars and two discharge pressures about 350 bars and 525 bars. CAPEX about 750 €/Nm^3 and OPEX about 7% of investment costs per year.
- 1500 kg of hydrogen stored at 350 bars of pressure. CAPEX about 400 €/kg of hydrogen and OPEX about 1% of investment costs per year.
- 800 kg of hydrogen stored at 525 bars of pressure. CAPEX about 760 €/kg of hydrogen and OPEX about 1% of investment costs per year.
- 2 hydrogen dispensers with two nozzles each, which are considered heavy duty vehicles according to SAE J2601-2. Flow rate of 60 g/s or 3.6 kg/min. CAPEX about 75,000 € per unit and OPEX about 3% of investment costs per year.
- 20% of the total equipment costs in civil works and mechanical, gaseous, electrical and control integration systems.

According to the previous data, the CAPEX of the hydrogen production plant and the hydrogen refuelling station would be about € 9.46 million.

It has been considered as revenue all the money that the underground mining company is currently paying for diesel fuel and all that can be saved from the necessary electricity for mine ventilation. The main details of the revenue are the following:

- It is considered that mining vehicles have a consumption about 20 l/h of diesel per unit. Given this assumption, we calculate a consumption about 480 l/day/machine. For 40 machines, the consumption would be about 19,200 L/day and about 6,336,000 l/year. Estimating the diesel price in 0.785 €/l (which is the current diesel price), the hydrogen production plant and the hydrogen refuelling station would produce revenues about € 4,973,760 per year.
- It is considered that the ventilation needs are reduced from 526.5 m^3/s to 230 m^3/s due to the use of fuel cell vehicles indoors (reference: Turquoise Ridge Gold Mine in Nevada. The installed power of diesel machinery is 9304 Hp; if it is divided by 40 machines considered, a unit power would correspond to 232.6 Hp. This means that it is necessary to use approximately a 60 kW fuel cell system and 85 kWh ion-lithium batteries for each mining machine). The diameter of the ventilation tunnels is considered to be reduced from 6.1 to 4.27 meters (reference: Turquoise Ridge Gold Mine in Nevada). The annual saving obtained from the reduction in ventilation costs would be 21,900 MWh/year; multiplied by 40 €/MWh, it shows 875,000 €/year.

- An annual operation of 7920 hours per year (330 days, 24 hours per day).
- Electrolyser efficiencies that could range from 70% up to 76.5% (given a degradation of 2 μV per hour). This implies that more electric power to produce the same amount of hydrogen would be required (i.e. less hydrogen would be produced every year).
- An electrolysis stack replacement would be needed after 80,000 operation hours or after 10 years of use at full load, which implies an initial value of 30% the investment costs and would decrease at a rate of 1% per year from the first to the last year of the study.
- Oxygen use, waste heat recovery, benefits from reducing tunnel drilling diameters and removing ventilation fans have not been considered.
- 30% of the investment with own resources. 70% of the investment through a 10-year loan with the French System.
- Investment costs of the hydrogen range extender electric vehicle for 40 vehicles: € 12 million.
- Investment costs of the hydrogen production facility and the hydrogen refuelling station: € 9.46 million.
- Total investment including vehicles with hydrogen range extender, the hydrogen production plant and the hydrogen refuelling station: € 21.46 million.
- Cost of the diesel fuel replaced by hydrogen: 0.785 €/l.
- Electricity costs: 40 €/MWh.
- Personnel costs: 200,000 €/year.
- Gross Water Costs: 2.5 €/m^3.
- Land leasing costs: 100,000 €/year.
- WACC: 8%.
- Inflation rate: 1.5% per year.

Results

Results of the techno-economic assessment of the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender electric vehicles

Based on the centralized hydrogen generation plant and the hydrogen refuelling station previously defined, the study brings a Net Present Value (NPV) of € 12,051,391, an Internal Rate of Return of 17% and a payback period of 7.78 years. Fig. 3 shows the NPV based on the contribution per year. As shown in this Figure, the amortization is reached between the year 7 and 8.

Furthermore, a small decrease in the NPV can also be observed around the year 12 due to the replacement of the electrolysis stack. In the same way, a consumption of 6,336,000 l of diesel per year can be avoided, which means that it is possible to avoid generating up to 16,537 tonnes of CO_2 per year (1 l of diesel produces 2.61 kg of CO_2).

Sensitivity analysis of one variable at a time

It is crucial to carry out a sensitivity analysis of the key factors in order to assess the limiting conditions in the decision-making process. The parameters considered in the analysis have been the Net Present Value (NPV) variation based on the electricity price and the NPV variation based on the diesel price. It is not possible to make further sensitivity analyses due to the fact that other parameters such as operation hours or the facility size are determined by the captive fleet size and the underground mining company requirements. On the other hand, the electrolyser price is currently a good price; it would not be possible to alter this parameter a lot in the upcoming years because the alkaline electrolyser technologies are very mature and have been sold for a long time.

NPV variation based on the electricity price

The price of electricity was changed from 10 €/MWh to 80 €/MWh. A negative slope linear effect between the Net Present Value (NPV) and the electricity cost was obtained (Fig. 4). Furthermore, the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines would not be economically viable for electricity costs above 70 €/MWh; in other words, electricity prices lower than 70 €/MWh are needed in order to obtain a positive Net Present Value.

NPV variation based on the diesel price

The price of diesel fuel changed from 0.4 €/litre to 1.2 €/litre. A positive slope linear effect between the Net Present Value (NPV) and the diesel fuel cost was obtained with a Net Present Value of € 0 at 0.53 €/l. Therefore, the hydrogen production

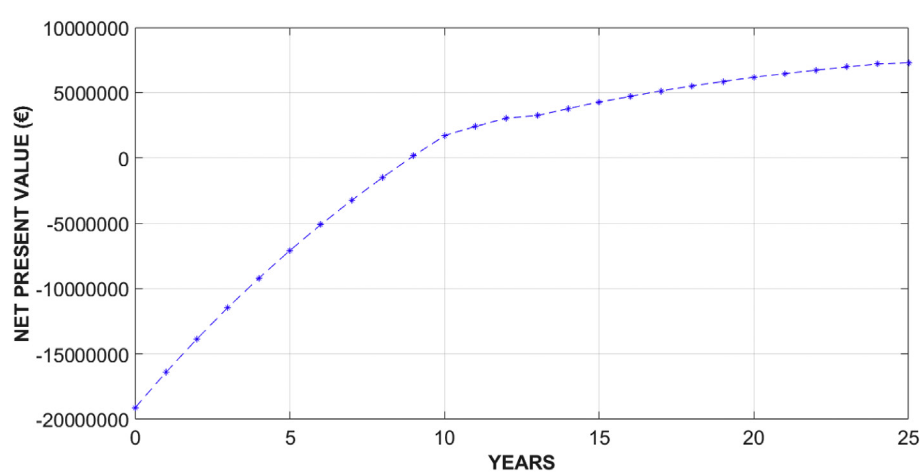

Fig. 3 – Net Present Value (€) vs. time (years).

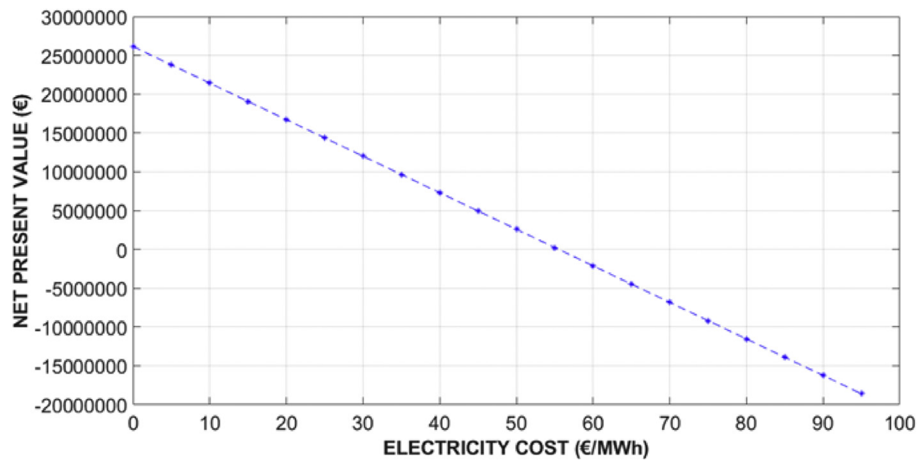

Fig. 4 – Net Present Value (€) vs. electricity cost (€/MWh).

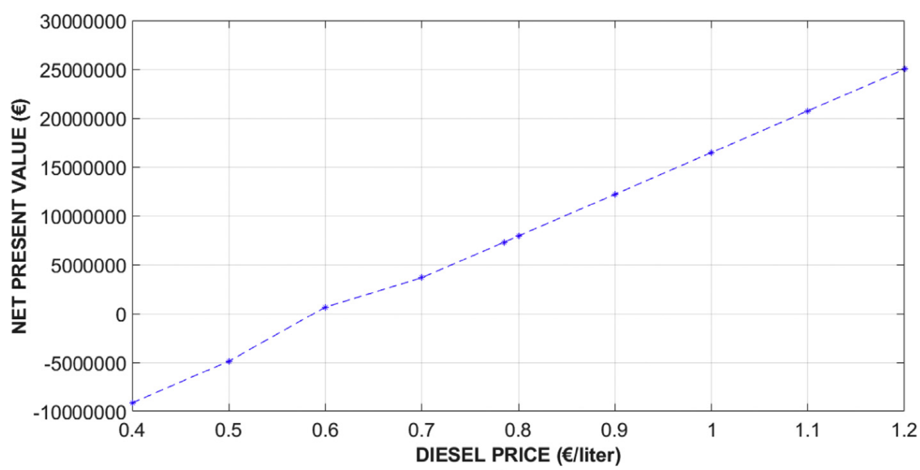

Fig. 5 – Net Present Value (€) vs. diesel price (€/litre).

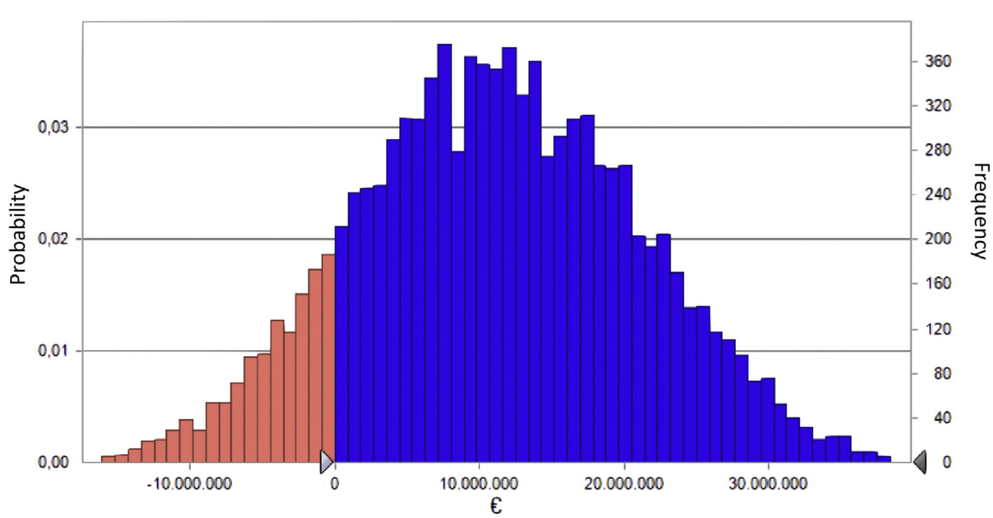

Fig. 6 – Probability distribution of the NPV sensitivity analysis.

Table 1 – Analysis of the sensitivity to Net Present Value.

Variable	Assumed Distribution	Ranges		Contribution to variance (%)	Rank correlation
		Min	Max		
Diesel Price (€/litres)	Triangular	0.4	1.2	63.1	0.78
Electricity Cost (€/MWh)	Triangular	10	80	36.9	−0.60

plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines would not be economically viable for diesel fuel costs lower than 0.53 €/l (see Fig. 5). In other words, diesel fuel prices higher than 0.53 €/l are needed in order to obtain a positive Net Present Value.

Multivariable sensitivity analysis of Net Present Value (NPV)

To complement the analysis of Net Present Value (NPV), the Oracle Crystal Ball tool [36–38] was used in this research work to analyse the effect of the following parameters: Diesel Price (€/litres) and Electricity costs (€/MWh). From the base case being studied, which describes a Net Present Value (NPV) of € 12,051,391, simulations were done in order to estimate the success probability of the project. Fig. 6 shows that, with a 95% of certainty, the NPV will be greater than zero for 86.33% of the studied cases (10,000 simulation cases).

In Table 1, it is shown that the Diesel Price affects in a 63.1% the Net Present Value variance and that the Electricity Cost has a significant effect on the Net Present Value (36.9%). These results are consistent with previous analysis which were carried out independently. The NPV is positively correlated with the Diesel Price, while the correlation is negative regarding the electricity price.

Diesel price volatility and logistics have the most significant impact on mining viability, but they are outside the control of most miners. The industry and the government have acknowledged the risks and environmental impact of fossil fuels and are supporting the adoption of renewable electricity and energy efficiency measures. Wind and solar PV are mature technologies that reduce the electricity costs of mines and the reliance on fossil fuels [39]. The use of renewable energies in order to produce green hydrogen and to replace the use of diesel in underground mining is the right decision to reduce emissions and be more competitive.

Conclusions

Based on the sensitivity analysis, it was observed that the electricity cost is a key parameter. The lower the electricity cost, the higher the Net Present Value of the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines. From this sensitivity study, it is concluded that the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines would not generate profits from an economic perspective for renewable electricity prices higher than 70 €/MWh. Similarly, the diesel fuel was considered a key parameter, as the higher the diesel fuel cost, the higher the Net Present Value of the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines. From this sensitivity study, it is also concluded that the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines would not generate profits from an economic perspective for diesel fuel prices lower than 0.53 €/l. Generally speaking, it seems clear that the use of hydrogen as a fuel for underground mining machinery could be profitable at present, showing a specific value for the NPV base case of € 12,051,391 and a 7.78-year payback.

Furthermore, the possibility of using the oxygen and the residual heat of the electrolyser and the possibility to obtain benefits from reducing tunnel drilling diameters and removing ventilation fans might generate an additional revenue in the income statement of the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines.

Working with the hydrogen production plant, the hydrogen refuelling station and the fuel cell range extender for electrical machines, it is also possible to avoid using up to 6,336,000 l of diesel per year. This means that the emission of up to 16,537 tonnes of CO_2 per year can be prevented. By selling this CO_2 right into a CO_2 market, we could obtain an extra revenue which would allow the NPV to become even higher (i.e. further incentive for investment).

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