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<Hydrogen opportunity in the mining industry in the context of decarbonization>

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Abstract

Hydrogen is a very known element that has various ways of usage, mainly for refining or chemical industries, as well as for ammonia production. It can also be produced by a diverse type of processes, like steam reforming from natural gas or coal gasification, but the way that is been produced releases a large quantities of carbon dioxide and other toxic gases for the atmosphere, that is why we call it as grey hydrogen.

In 2006 the European Commission has created a pathway initiative for the decarbonisation, highlighting the importance of sustainability and efficiency, leading us to produce renewable energy with zero carbon emissions instead of relying only on fossil fuels resources. After several years, in 2015, was settled a worldwide agreement in Paris. "The Paris Agreement sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2ºC and pursuing efforts to limit it to 1,5ºC. It also aims to strengthen countries' ability to deal with the impacts of climate change and support them in their efforts." [10].

The European Commission Green Deal, settled in 2019, reinforces the Commission's commitment to tackle climate and environmental related challenges by defining ambitious policies to decrease EU's greenhouse gas emissions during the next decades, a reduction of at least 55% until 2030 and 100% by 2050.

Today, more than ever, the search for efficient and sustainable carbon-free solutions is crucial. The green hydrogen has turned out to be the last piece of the puzzle, as it allows us to achieve the expected results. Green hydrogen is produced through a process of water electrolysis system using renewable energy as electric power. This topic has turned out to be more relevant as we are becoming more ambitions on climate action, we are talking about producing energy more clean, more affordable, resilient, and secure.

Hydrogen has the potential to decarbonize sectors that are difficult to decarbonize. In this paper we will analyse a mining facility, traditionally with a heavy consumption and present adequate solutions for decarbonization.

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Glossary

AEC	alkaline electrolysis cells
CCS	carbon capture and storage
CO2	carbon dioxide
ETS	emissions trading system
EU	european union
GHGe	greenhouse gas emissions
GJ	gigajoules
GWh	gigawatts per hour
H2	hydrogen
H2O	water
kg	kilograms
kgCO2e	kilograms of carbon dioxide emissions
km	kilometres
kW	kilowatts
kWp	kilowatts peak
LCOE	levelized cost of energy
MWh	megawatts per hour
MPa	megapascal
Nm^3/h	normal cubic meter per hour
O	oxygen
PEM	proton exchange membrane
PV	photovoltaic
ROM	run-of-mine
SDG	sustainable development goals
SOEC	solid oxide electrolysis
tCO2e	tons of carbon dioxide equivalent
toe	tons of oil equivalent
USD	united states dollar

1. Introduction

We are evolving into an energy transition, a transformation of the energy sector from fossil fuels to a renewable and clean energy sources endorsed by a global community striving for a sustainable future, this was accelerated due to coronavirus situation and the subsequent influence on oil prices as well as the evidence that the system could be managed even in presence of high-level penetration of renewables. The energy transition's core is the necessity to reduce energy-related carbon dioxide (CO2) emissions to mitigate the effects of climate changes helping meet the climate goals set in the Paris Agreement, decarbonisation of the energy sector requires an urgent action on a global scale.

Paris Agreement, settled in Paris in December 2015, was one of the most important and ambitious global climate meeting ever assembled by 196 parties, a new legally valid agreement, and enforceable agenda for an internationally organized effort to tackle climate change. The objective is to reduce the global greenhouse gas emissions to levels that would prevent global warming from increasing more than 2 degrees Celsius on pre-industrial levels and chasing efforts to limit it to 1,5ºC in this century. It also aims to improve countries capability to deal with the impacts of climate change and help them in their efforts. To do so, our only chance is decarbonisation, that represents the reduction or the elimination of carbon dioxide emissions from energy sources, replacing fossil fuel energy systems by low or zero carbon energy sources. Essentially, this can be done through a process of replacing fossil fuel technologies for systems that use electricity, preferably resultant from renewable sources, we call this, electrification.

Also in 2015, the Sustainable Development Goals (SDG) were adopted by United Nations. That was a universal call to ensure that by 2030 all people enjoy peace and prosperity, it is a purpose to change the world for the better. There are 17 integrated sustainable development goals, we can realize that one action in one area will affect outcomes in the others, and that progress will balance social, economic, and environmental sustainability. There are two SDG that we want to quote, affordable and clean energy, and climate action.

One bold action of the early years was the European Union's Green Deal, a new strategy for the transition of the EU economy to a sustainable economic model. Presented in December 2019, this will be achieved by transforming climate and environmental challenges into opportunities around all policy areas to become a climate neutral place by 2050 and a 50% - 55% cut in carbon dioxide emissions by 2030, resulting into an improved life's quality with energy more affordable and cleaner. The EU Green Deal aims to improve the use of resources more cost-effective by stopping climate change and make the economy circular, clean and more efficient, making this transition just and comprehensive for all. This transition can be done mainly via 4 vital pillars, the first pilar is based on the proposal of the upcoming transformation that must ensure an effective carbon price, by establish the European Union emission trading system (ETS) on the new sectors, and by making sure that EU countries will proper tax the emissions not covered by the ETS, making it align with climate goals. Second, the sustainable investments strategy, green investments should be properly promoted by incentives and supported by EU funds to help companies switching their current technologies and by incentive private investments. The third pillar is represented by a new European Union industrial strategy, the concept of overcome the challenge by creating the european economy sustainable while preserving the competitiveness of the industry, supporting companies to grow up by providing the right conditions. Lastly, the fourth pillar is the Just Transition Mechanism (JTM), planned as compensation measures to support the unavoidable effects of the transition, the undesirable social consequences of climate policies will be taken in consideration. In specific, industries with high employment that could be harshly impacted by the transition, like coal mining or regions with high greenhouse gas emissions industries, they will be financed by the Just Transition Fund (JTF). Will present next the European Union Green Deal action plan and the various policy areas that supports:

Figure 1 - Policy areas of the EU Green Deal [25]

Currently the energy system is considered inflexible and economical inefficient to provide a climate neutral economy. So, it is crucial that, to reach the climate neutrality by 2050, a strategy will be required, for that, the EU commission proposes a new strategy for an energy system integration. The strategy has three vital elements, first, energy efficiency, an increase of energy efficiency will reduce the demands from energy production and investment costs. Second, electrification, since we are chasing the climate neutrality and decarbonisation, the upcoming electricity demand is meant to increase, in addition, the prices of renewable electricity will reduce. So, we need to encourage the use of renewable electricity, especially in highly fossil fuel reliant industries. Finally, the use of renewable and low-carbon fuels for end-use applications where electrification or heating are not viable. Renewable gases or liquids and low-carbon fuels, like hydrogen, can provide different storage solutions for the energy generated from renewable sources.

Hydrogen has the capability to perform a vital role on climate neutrality, it is the most abundant chemical element in our planet, with unique properties, its potential as an efficient energy carrier makes it a key piece in the puzzle on energy solutions. The progress on hydrogen technology solutions have now progress to a point where hydrogen is emerging as a viable option for uses in transportation, heating, grid storage and industrial applications. Hydrogen can be produced using a several different processes, such as chemical conversion processes, like steam methane reforming (SMR) or coal gasification, or by water electrolysis process, that uses electricity to split water (H2O) into hydrogen and oxygen. Each hydrogen production process has a specific denomination by a specific colour, it depends on its production method. Hydrogen produced through steam methane reforming for example, is called grey hydrogen and this is the most dominant hydrogen type on the market and the cheapest. We will present next the most crucial types of hydrogen production types:

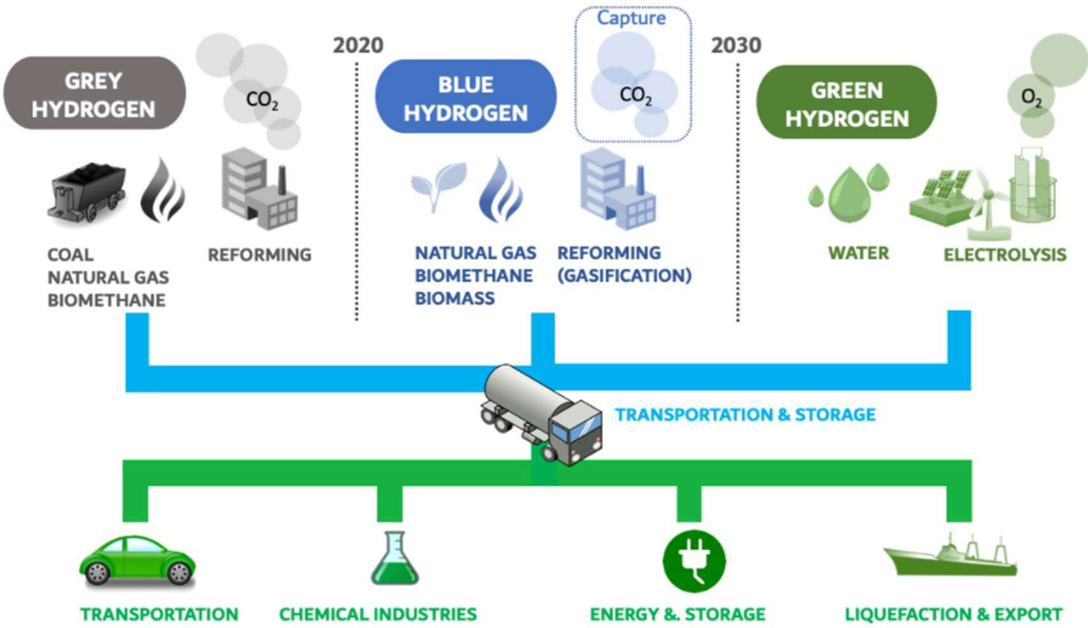

Figure 2 - Visualisation of 3 types of hydrogen production routes and their denomination by colour [4]

Energy carries such as hydrogen will have a crucial role on many different applications, such as heavy transport and heavy industry. Hydrogen is still very expensive, so it can be used mainly where there are no low or zero carbon emissions alternatives and where other benefits compensate the higher costs. Since hydrogen have a very high energy density, heavy transports like aviation, trucks or trains will profit from hydrogen usage, in the other hand, cars already have cheapest alternatives with zero carbon emissions. Hydrogen is a versatile gas that can provide very high temperatures, so, for heavy industries such as steel and cement, that represents a substantial part on global carbon emissions, hydrogen can be a vital alternative.

The mining sector itself is basically one of the responsible for the growth of greenhouse gas emissions globally, taking a considerable impact on climate change. We expect that over the years, mines can be fully decarbonized through energy efficiency, electrification, and renewable energy with the proper investments. The mining industry generates tons of carbon dioxide equivalent of greenhouse gas emission over the year, and so, to implement the conditions of Paris Agreement, a serious effort will be required to seriously reduce the GHG emissions by 2050. There are already some solutions to implement at several mine types, but support and development is still needed to overcome the barriers that will be encounter over the implementation.

Hydrogen brings a whole range of opportunities in the mining industry, it can efficiently power heavy machinery, fuel cargo vehicles and company cars, as also to energy storage to generate electricity, even if some alternatives will not be economically the best option on the next few years. There is already implement into the mining sector an 800kW mining trunk using fuel cells technology, this fuel cells uses an electrochemical reaction between oxygen and hydrogen fuel to produce electricity with vapor and heat as resultant emissions.

Figure 3 - Anglo American ultra-heavy-duty mining truck to be retrofitted with 800kW of fuel cell modules [11]

Hydrogen is the perfect choice to tackle climate changes, a way to reduce the global greenhouse gas emissions to levels that would prevent global warming. Many researches and experiments still be needed, but there is already a certain clean alternative that we already have, the green hydrogen.

On this work we begin by presenting what green hydrogen is and all the process required to produce it, the water electrolysis technologies . In the chapter number 3 we will introduce the proposed case study, the mine energy consumptions provided by the company that manages the Panasqueira mine, including consumptions for heating diesel, diesel for transportation and electricity, as well as a global energy and emissions indicators, we will also conduct a study to understand the renewable resources available nearby to provide power for the water electrolysis technology, as well as an ongoing photovoltaic power plant for mine's self-consumption. On another section of the chapter 3 we will also present the different water electrolysis technologies, providing special interest to Proton Exchange Membrane (PEM) technology. Followed by the mine's hydrogen needs, where we predict the hydrogen quantity required, the hydrogen production technology, electrolyser location and the average power consumption, as well as the hydrogen fuelling, storage, and transportation equipment. In the last chapter, we will present a techno-economic analysis. Initially presenting the projections for the green hydrogen production costs as also the carbon prices over the next several years, as well as the costs evaluation, comparing over the years, the fossil fuel and electricity usage with the green hydrogen solution.

2. Green hydrogen

Decarbonisation the planet is the main goal that European Union set until 2050, and green hydrogen is one of the vital recipes to accomplish it, making it more sustainable and efficient. Green hydrogen is generated by a chemical process known as electrolysis, using electrical energy on water to split hydrogen from oxygen, the electrical current must come from renewable source, like wind or solar, allowing to create hydrogen without any carbon dioxide emissions.

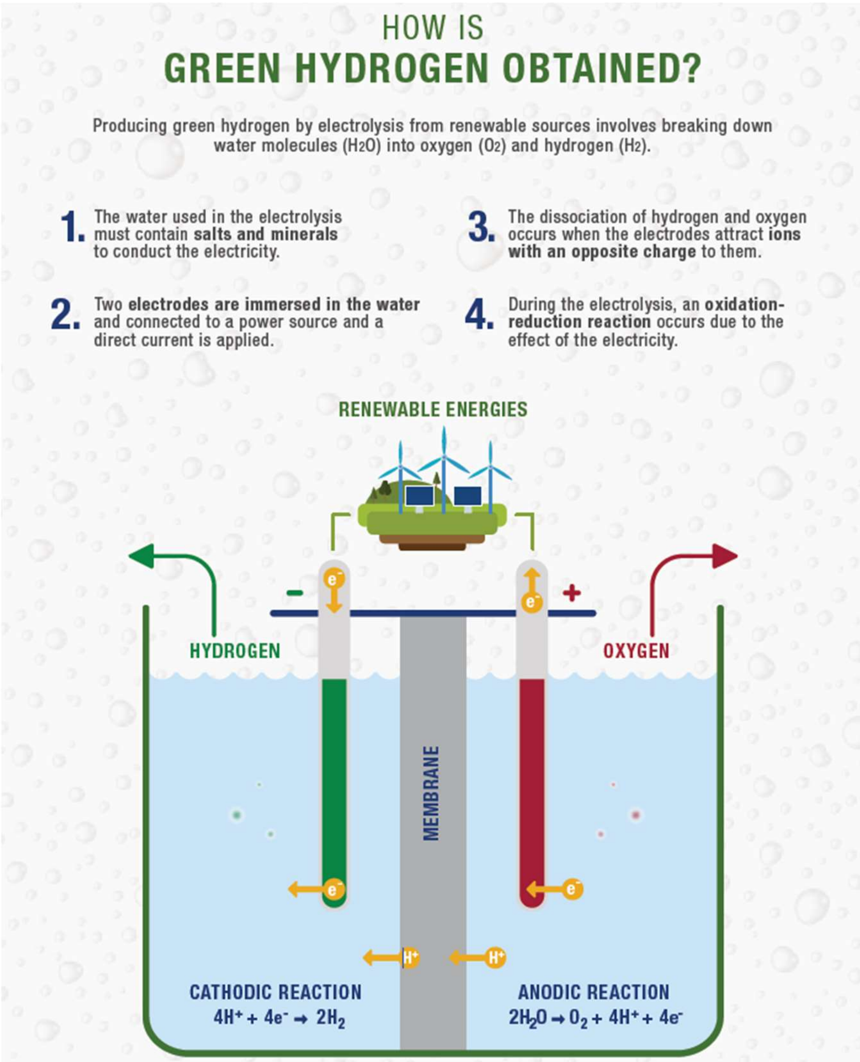

Figure 4 - Producing green hydrogen by electrolysis from renewable sources [16]

Creating green hydrogen by electrolysis from renewable sources will save tonnes of carbon dioxide equivalents (tCO2e) emissions released from other hydrogen production techniques, like steam methane reforming (SMR) that uses fossil fuel to produce hydrogen (grey). The green hydrogen production costs are still high comparing with blue or grey, however, is dropping with renewable energy prices and the electrolysers are becoming cheaper.

There are plenty uses for green hydrogen, for example, we can power fuel cells for transportation and electricity, or we can blend it with natural gas for heating or thermal power, or even for other energy carriers like ammonia.

Like any other gas, hydrogen can also be transported, compressed, and stored in high-pressure tanks or dedicated pipelines, although, the volume needed for hydrogen is higher compared with other gases, for hydrogen, is required an 700bar pressure tank. As in liquid state, hydrogen requires cryogenic temperatures of minus 252,8 degrees Celsius because of the boiling point. Since hydrogen is a highly flammable gas, transportation or storage could be hard and risky. The best option is to convert hydrogen into ammonia and after reaches the destination or intends to use it, do the reverse process, this method is a lot safer and cheaper but there are some energy losses in the process.

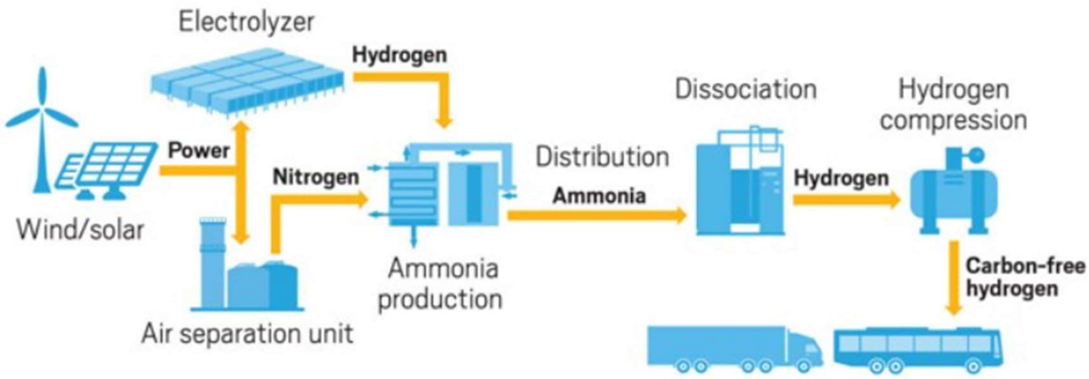

Figure 5 - Hydrogen transportation alternative using ammonia [3]

We believe that green hydrogen has a vital role on reaching decarbonization of the energy system, mainly heavy industry as it is the case of mining industry.

2.1. Water electrolysis

In this chapter we will analyse the hydrogen production through water electrolysis and evaluate whether there is or not enough renewable sources for the energy needed.

There are many ways to produce hydrogen. The hydrogen is referred as grey or brown if the primary source is fossil fuels or coal, is blue if produced by natural gas reforming with carbon capture and storage (CCS), it is named turquoise if created through natural methane pyrolysis into hydrogen and solid carbon. But still, to reach the goals of 2050 we need to obtain hydrogen by the most sustainable and clean way, which is the green hydrogen.

For that, hydrogen must be obtained by water electrolysis, using an electrolyser powered by a renewable energy source. This process dissociates hydrogen (H2) from oxygen (O) under electric influence. So, that only emits oxygen without any carbon emission generating hydrogen (green).

There are a few water electrolysis technologies that can be classified based in their electrolyte or even how they operate. We will present three: Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane (PEM) and Solid Oxide Electrolysis (SOEC).

2.2. Water electrolysis technologies

In this section we list the different water electrolysis technologies that are available in literature:

Table 1 - Water electrolysis technologies [14]

Alkaline Electrolysis Cells (AEC)	• **Most mature** and widely deployed • **Cheapest** (non-precious metal catalysts, e.g. nickel) • Liquid alkaline electrolyte • Longest lifetime • Operate up to ~80°C and 1-30 bar • 50-70% efficiency (system) • **Not suited to intermittent input** (low load factor: minimum 20-30%)
Anion Exchange Membrane (AEM) **Proton Exchange Membrane** (PEM)	• Uses pure water • Solid electrolyte • **Smaller footprint** • **Higher pressure** output (up to 100-200 bar in some systems) • **Suited to flexible operation** (fast start/stop & ramp up/down) • 60-75% efficiency • Uses (expensive) **platinum** metal group based catalysts (Pt, Ir)
Solid Oxide Electrolysis (SOEC)	• Least mature technology (& currently **most expensive**) • Low cost ceramic electrolytes • Operate at **high temperature** (700 to 900°C), using steam • 75-85% efficiency • Require a heat source (ideally **waste heat**) • **Can operate in reverse**, as a fuel cell • High operating temperatures degrades materials (so **shorter lifespan**) • Output at ambient pressure

2.3. Proton Exchange Membrane (PEM)

Proton exchange membrane, also known by PEM, it will be the water electrolysis technology chosen for this project. Besides all the reasons presented before, this choice is mainly because of the capability that PEM have with flexible operations. One of the problems on the hydropower and wind power plants is the lower flexibility, so this way we can provide a better operation.

PEM water electrolysis was developed in 1966 by General Electric Co., have many advantages, like high pressure operations (100 – 200 bar), low gas permeability and high proton conductivity. Using pure water to operate, in terms of environmental impact or sustainability, PEM is the most suitable to generate pure green hydrogen from renewable energy with 99.9995% purity on-demand. Also, have other advantages like high efficiency (60 – 75%), small footprint and operates under lower temperatures (20 – 80 ºC).

Like mention before, PEM is suited for flexible operations, it provides fast response times and production flexibility, have a 0 to 100% variable output, a cold start less than 5 minutes and a full ramp up or down in seconds what make him ideal for hydrogen generation utilizing renewable power sources. Besides that, it requires minimum maintenance, a scalable modular design and have remote monitoring and control.

Figure 6 - PEM electrolyser M series containerized by Nel [18]

3. Case study the mining industry

Hydrogen (H2) is one of the most abundant elements on planet earth. It is a gaseous chemical element characterized by being colourless and odourless, being denser than air, it is also the lightest element on the periodic table. Hydrogen, although it has been used for many years, has been the target of greater attention in several sectors in recent years, especially in the energy sector.

Hydrogen plays a fundamental role in energy decarbonisation, having a high contribution to achieving the goals imposed by the Paris Agreement and the EU Green Deal. The contribution of hydrogen to the reduction of greenhouse gas emissions allows us to take a path towards carbon neutrality, which is an international commitment that we want to achieve. The electrification of the energy system also offers an alternative to decarbonization, although for sectors such as heavy industry, more specifically, the mining industry, it is not the most effective resource. Here hydrogen, more specifically green hydrogen, plays a crucial role in energy decarbonisation and the climate crisis. Becoming an increasingly accessible resource, green hydrogen has gained greater economic viability, as would be desired.

Not existing in nature in its pure state, it must be obtained through various processes. The most used process is reformation, which works by applying high temperatures, in which steam reacts with a hydrocarbon fuel, such as natural gas, to produce hydrogen. As the most widely used method, it releases carbon dioxide into the atmosphere, thus designating hydrogen as grey. Alternatively, we have electrolysis, this process uses an electrolyser that uses an electric current to separate water into hydrogen and oxygen. If the electric current comes from a renewable resource, the hydrogen obtained is called green.

Green hydrogen is a fundamental tool to decarbonise sectors that are difficult to decarbonise, such as energy-intensive industries, specifically the mining industry, thus providing a contribution to the carbon neutral paradigm with the reduction of greenhouse gas emissions and strengthening the competitiveness of these industries.

The mining industry, being an energy-intensive industry, has high levels of carbon dioxide emissions into the atmosphere, and rapid intervention is therefore needed to make this sector more efficient and sustainable. The use of green hydrogen in the mining industry is a clean alternative to replacing diesel in various sectors, such as heating, transport, and machinery, as hydrogen can be used both by combustion and by fuel cells.

From the various mining industries existing in Portugal, such as ALMINA – Minas do Alentejo S.A. or Somincor – Sociedade Mineira de Neves Corvo SA, Mina da Panasqueira was chosen for this work. This choice was mainly based on the renewable resources already existing around the mine, thus making the process of creating green hydrogen more achievable.

The Panasqueira Mine, operated since 1896, located in the district of Castelo Branco, more specifically on the limits of the municipalities of Covilhã, Fundão and Pampilhosa da Serra, with a total area of 21km^2, and it associates 42 mining concessions. It is located on the southern slope of Serra da Estrela, more precisely in the massif of Serra do Açor. The mining centre currently operated by Sojitz Beralt Tin & Wolfram (Portugal) S.A. is in the village of Barroca Grande, where today all mining activity is concentrated.

We are now going to present the data provided by the company that operates the Panasqueira mine. The following tables show the global energy consumption recorded during 2019:

Table 2 - Monthly distribution of energy consumed in 2019 [2]

BTW	Consumo de Energia Total									Total		
	Eletricidade			Gasóleo			Gasóleo de Aquecimento					
2019	GJ	tep	tCO_2e	GJ	tep	tCO_2e	GJ	tep	tCO_2e	GJ	tep	tCO_2e
Jan	5.420	324	708	2.453	58,6	182	335	8,01	24,8	8.209	390	914
Fev	4.858	290	634	2.127	50,8	157	308	7,36	22,8	7.293	348	814
Mar	5.601	335	731	2.402	57,4	178	367	8,76	27,1	8.370	401	936
Abr	4.391	262	573	1.844	44,0	136	270	6,45	20,0	6.505	313	730
Mai	4.974	297	649	2.382	56,9	176	345	8,23	25,5	7.701	362	851
Jun	4.592	274	599	2.111	50,4	156	319	7,63	23,6	7.022	332	779
Jul	4.500	269	588	2.335	55,8	173	298	7,12	22,1	7.133	332	782
Ago	2.976	178	389	1.218	29,1	90,1	153	3,65	11,3	4.347	210	490
Set	4.657	278	608	2.127	50,8	157	298	7,11	22,0	7.081	336	787
Out	4.700	281	614	2.199	52,5	163	276	6,59	20,4	7.175	340	797
Nov	5.377	321	702	1.901	45,4	141	292	6,98	21,6	7.569	373	864
Dez	4.170	249	544	1.468	35,1	109	170	4,06	12,6	5.808	288	666
Total	56.216	3.357	7.339	24.566	587	1.818	3.430	81,9	254	**84.212**	**4.026**	**9.411**
%	66,8%	83,4%	78,0%	29,2%	14,6%	19,3%	4,07%	2,04%	2,70%	-	-	-

By analysing the above table, during 2019, BTW consumed a total of 4,026toe. The graph below shows the evolution of energy consumption during the year under analysis:

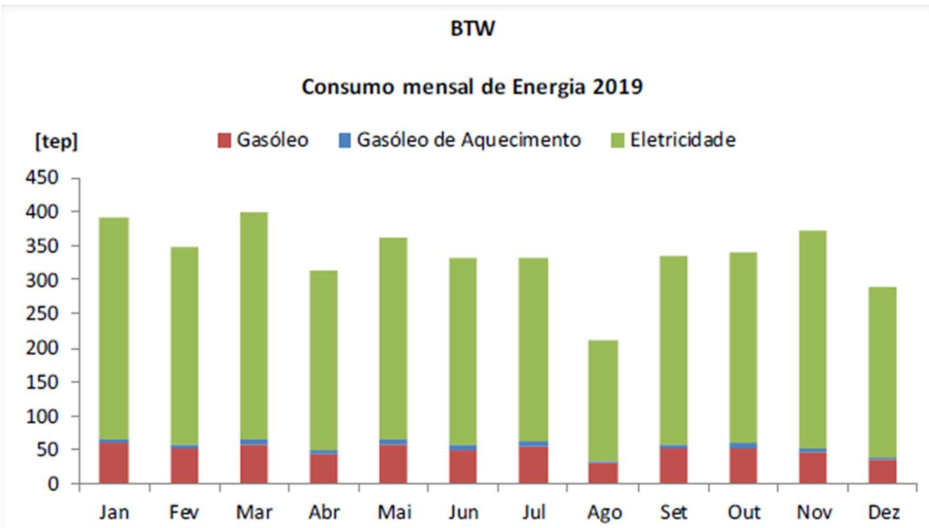

Figure 7 - Monthly energy consumption in 2019 [2]

Regarding the year 2019, the month with the highest consumption was March, with 401toe, and the month with the lowest consumption was August, with 210toe. This year recorded an overall increase of 6.38%, compared to the reference year (2017). The graph in which it is possible to observe the variation in energy consumption in the year under analysis is presented below, when compared to the reference year of the energy audit (2017).

Through the data provided above, electricity was the predominant form of energy, both in terms of consumption and cost. In 2019 electricity represented 83.4% of consumption, followed by diesel with 14.6% and heating diesel which accounted for 2.04%%. Regarding the costs of this same year, electricity represented 63.5% of the costs, followed by diesel which represented 32.5% and heating diesel with 3.97%.

Regarding CO2 emission, the Panasqueira mine presents the following situation illustrated in the table 3, describing the data from 2019:

Table 3 - Greenhouse gas emissions 2019 [2]

Greenhouse Gas Emissions	tCO2e	%
Plant	3.495	37,1%
Mine	4.580	48,7%
Water Treatment	1.336	14,2%
Total	9.411	
Average kgCO2e/mtu (2012-2019)	119,49	kgCO2e/Mtu

As we can see from the table presented above, greenhouse gas emissions represent a total of 9,411tCO2e per year. The mine was the main responsible, with 48.7% of emissions, followed by plant with 37.1% and water treatment with 14.2%.

We present below the CO2 balance for the year 2019:

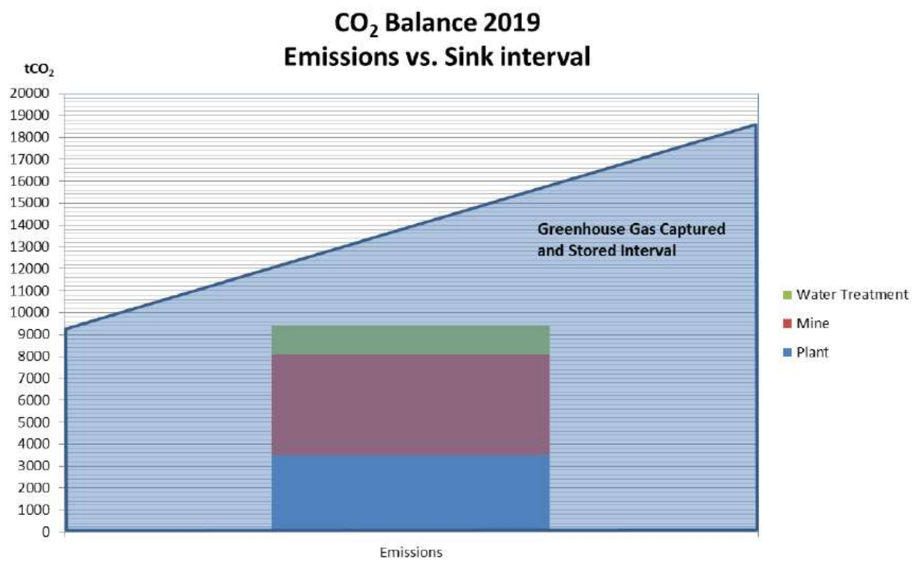

Figure 8 - CO2 Balance 2019 [2]

Our goal is to find a strategy to decarbonize the Panasqueira Mine using green hydrogen. The reasoning for that is the intensive consumption industry as described in section 3.1 and by knowing that great part of consumption is dedicated to extract pollutant gases from inside the mine. Hydrogen if used inside de mine will avoid pollutant emissions and the energy that is needed to extract the pollutant gases.

The objective is to find the best solution from all the options and alternatives to make the mine cleaner and more efficient.

3.1. Mine energy consumptions

In this section we will analyse the different types of consumption from the various sectors of the mine, which are, transportation, machinery that works inside de mine for extraction of metal ore, beneficiation, and processing solid minerals which in this case is the tungsten.

HEATING DIESEL

The distribution of heating diesel consumed is allocated according to the production of ROM (run-of-mine). Following the past few years, the consumptions are distributed as follows: in the year of 2018 around 111 tons of heating diesel, that represent around 4.763GJ of energy, 114 of tons of oil equivalent (toe) and 352 tons of CO2 equivalent (tCO2e), this year comparing to the reference year of 2017, was very similar, less 3,92%. On the following year (2019), the consumption has reduced to 80.1 tons of diesel consumed, 3.430GJ of energy, 81,9 of toe and 254 tCO2e, this situation occurs because there was no consumption on the second trimester, representing a 25% decrease of consumption comparing to the reference year (2017). The next chart presents the monthly consumption over this year:

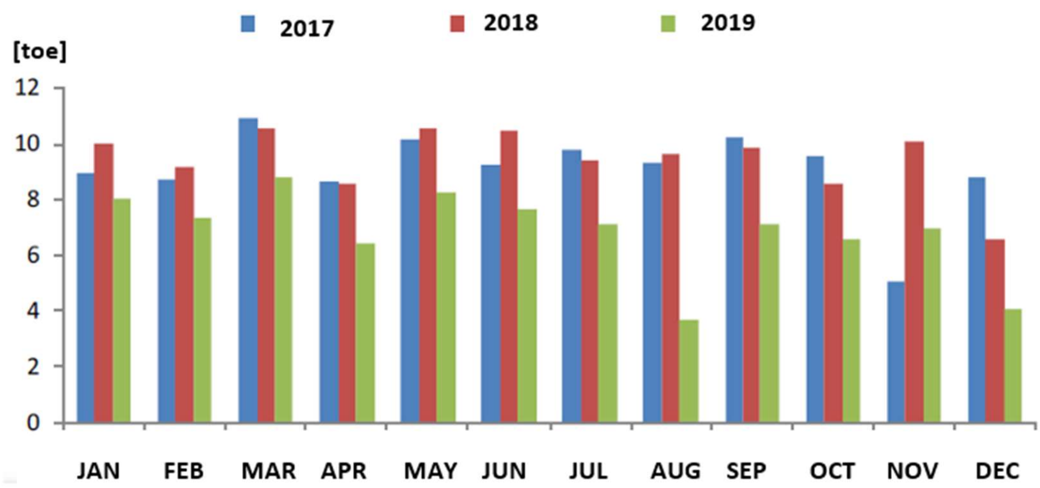

Figure 9 - Monthly heating diesel consumption [2]

During the year of 2020, the available data represents the first 6 months, 53,4 tons of heating diesel consumed, that represents 2.287GJ of final energy and 54,6 tons of oil equivalent, comparing to the similar months of reference year (2017) and 2018, we can expect that 2020 will be identical.

For study we estimated that the consumption during the following years will be the average of the available data. We will assume that tons of the heating diesel consumed over a year is approximately between 115 tons that generates about 5.000GJ of final energy and 120 tons of oil equivalent. This means the production of about 365 tCO_2e.

DIESEL FOR TRANSPORTATION

The mining machines for transportation, cargo vehicles for the extraction and company cars are fuelled by diesel.

In 2018 over the year was consumed 589 tons of diesel, that represents about 25.212GJ of final energy and 602 tons of oil equivalent. In 2019 there is a diesel consumption of 574 tons, 24.566GJ of final energy and 587 tons of oil equivalent. So, comparing to the reference year (2017) we have an increase of 7,18% in 2018 and 4,43% in 2019. The next chart, figure 10, presents a monthly comparison for the three years.

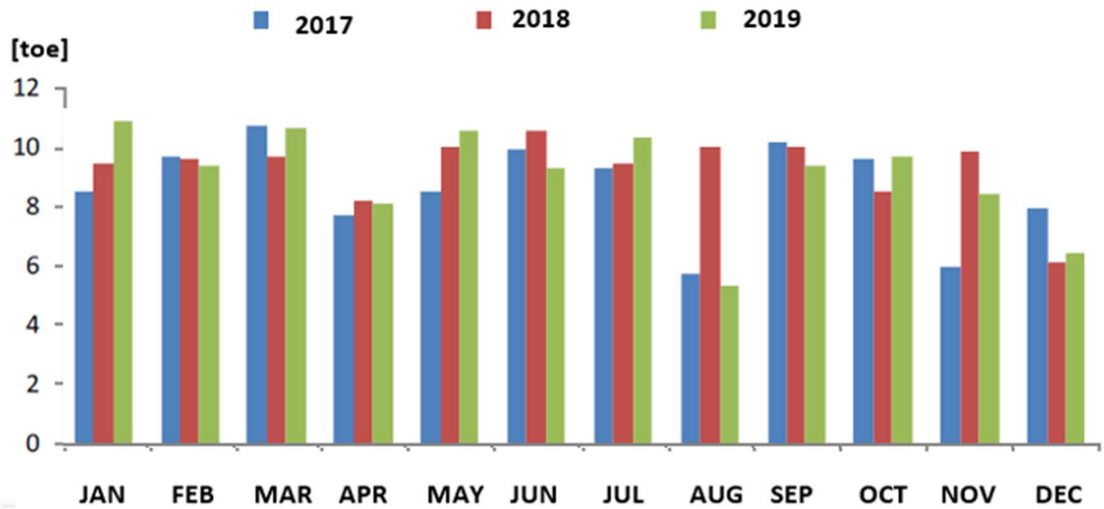

Figure 10 - Monthly diesel consumption [2]

Looking at the year of 2020, the first semester presents a total diesel consumption of 276,60 tons, this represents on the homologue year of 2017 a reduction of 5,1% on diesel consumption. So, for further analysis it is expected that the consuming of diesel on mining machines, cargo, transport, and company vehicles will present an estimated consumption of 550 tons of diesel, which means 23.500GJ of energy and 560 tons of oil equivalent. This indicates that are released per year approximately 1750 tons of CO_2 emissions to the atmosphere.

ELECTRICITY

The mine also presents a huge electricity consumption per year. Like told before, in 2019, the second trimester on the mine, the production has stopped, but still, electricity has been consumed for the main and safety equipment and other purposes. On the next chart, figure 11, we present a comparation of de monthly consumption of electricity over the first semester:

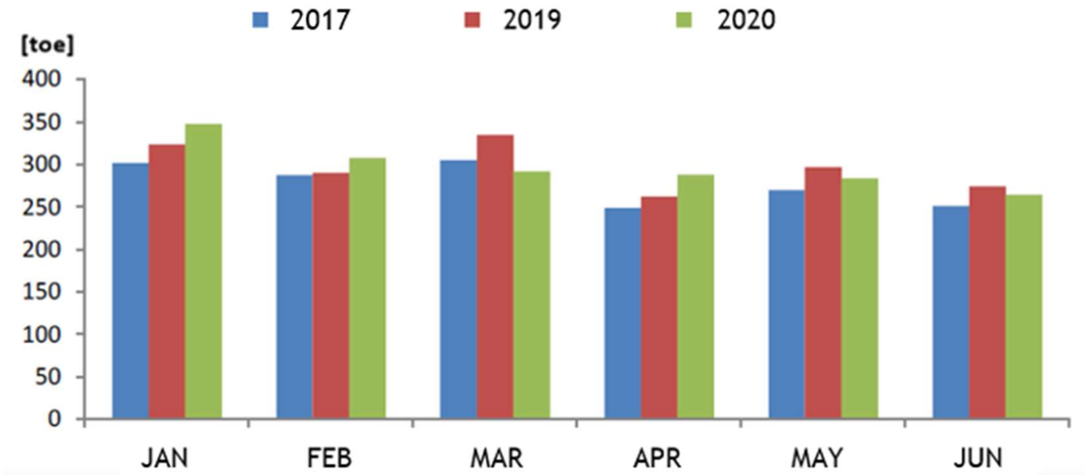

Figure 11 - Monthly electricity consumption on 1st semester [2]

Overall, in 2018 the mine of Panasqueira consume 15.991MWh of electricity and in 2019 there was 15.615MWh of consumption. So, we expect over the years that the electricity consumed will be around 16.000MWh, that represents about 58.000GJ.

3.2. Overall energy and emissions indicators

In this section we will analyse the overall production over the past four years on the first semester. Table 4 presents the figures for overall consumption as well as the tons of oil equivalent (toe) and the greenhouse gas emissions (GHGe).

Table 4 - Energy and emission indicators

	PRODUCTION	ENERGY		GHGe
	tons	GJ	toe	kgCO2e
2017	390.740	42.623	2.016	4.729.444
2018	399.211	46.008	2.193	5.131.192
2019	389.946	44.298	2.127	4.965.513
2020	340.524	43.999	2.121	4.944.411

On the first semester the overall production was almost 400.000 tons of ROM (run-of-mine) materials plus waste, needs about 45.000GJ of final energy, what represents approximate 2.100 tons of oil equivalent. On 6 months the Panasqueira mine generates about 5.000.000kg of CO2 emissions.

Also, after the analysis from the data from the last years, we can demonstrate de overall distribution of the consumptions from the primary energy (toe) represented on the next chart:

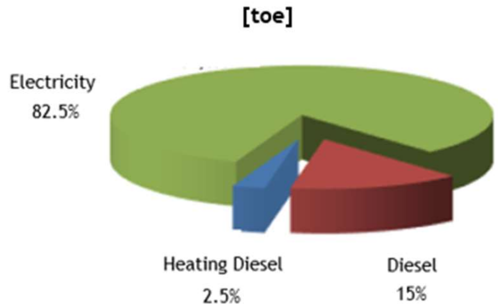

Figure 12 - Annual primary energy distribution [2]

From the graphical analysis presented in the figure 12 we can see that the main consumption is electricity.

3.3. Renewable resources nearby

To produce green hydrogen, it is mandatory to have renewable power source available, preferably nearby, mainly for investment costs. It will depend how much power we will need for the electrolyser, so it is fundamental we study all the possibilities that exists around.

SOLAR PHOTOVOLTAIC SYSTEM

There is already a foreseen project of a solar PV plant to be developed during 2021. The plant is planned for self-consumption in the Panasqueira Mine and will be located at the village of São Francisco de Assis. This plant will haves a power peak of 2.523,96kWp installed, that represents about 3.437.515kWh per year plus an excess of production of 720.244kWh/year, in a total of 4.157.759kWh/year. We are talking approximately about 15.000GJ produced every year, that represents about 20% of the total energy required for the mine.

Figure 13 – Location from solar PV system at Panasqueira mines [2]

Figure 13 presents the future solar plant that will be built nearby the mine. As explained, this will contribute to around 20% of the consumption needs.

HYDROELECTRIC POWER PLANT

Near the Panasqueira mine there is one small hydroelectric power plant and one large.

Starting with Barroca hydroelectric power plant, is located at Fundão district, it is a run-of-river hydropower in Zêzere river, with a power capacity installed of 1900kW working since December of 2005 that can generates approximately 5,91GWh per year.

Figure 14 – Hydroelectric power of Barroca [1]

We also have a large hydropower, localized at Pampilhosa da Serra, that started working at the year of 1943, the hydroelectric power of Santa Luzia it is a reservoir hydropower plant, it has 24,4MW of maximum power capacity and can generate 54GWh per year.

Figure 15 - Hydroelectric power of Santa Luzia [6]

To conclude, the hydropower available nearby the mine, presents approximately a total of 59,91GWh per year of power generation, that represents 215.676GJ of energy.

WIND POWER GENERATION

There also have five wind power generation plants nearby Panasqueira mine. The next table we presents the power and the annual production from each one approximately:

Table 5 - Wind power parks

	WIND PARKS				
	ALTO ARGANIL	CHIQUEIRO	GARDUNHA	TOUTIÇO	VIDUAL
POWER INSTALLATION (MW)	36.0	4.0	114.0	102.0	1
ANNUAL POWER GENERATION (GWh)	105	8,7	227	211	0,01

So, we are talking about near 257MW of power installed on this wind parks, that producing about 551,71GWh per year, that means 1.986.156GJ of energy per year.

Figure 16 - Wind power park of Gardunha [20]

The power installed on Chiqueiro and Vidual is residual when compared with the other wind power plants.

3.4. Mine hydrogen requirements

From the analysis on the mine consumptions, it is expected that the heating diesel and the diesel consumption on the mine by the mining machines, transportation, cargo, and company vehicles, represents about 115 tonnes of heating diesel plus 550 tonnes of diesel for transportation, so approximately 665 tons of diesel consumed over one year. This represents a total of 28500GJ of energy required per year. If we look too a per day consumption, we expect around 78GJ, that signifies 3.25GJ per hour.

We need to estimate how much H2 will be needed to replace the diesel consumption by a green source. We know that 1kg of hydrogen contains 33.33kWh of energy [lower heating value (33.33kWh) = higher heating level (39.4kWh) – heat of vaporization of water (6.1kWh)]. So, if we predict that we need 3,25GJ of energy per hour, this means we need 902,78kWh, that represents 27kg of hydrogen required per hour, 236.520kg per year. To further analysis, 27kg of hydrogen represents 300,24Nm^3 per hour. This process also requires approximately 9 litres of water per 1kg of hydrogen and produces 8kg of oxygen.

3.5. Hydrogen production solution

There are already several companies that manufacture water electrolysis technologies, we analysed a specific company, the Nel Hydrogen, company that presents available figures that are needed to our analysis. Nel presents some solutions either for hydrogen production as for fuelling or fuelling storage. From the calculations, we know that will be required an electrolysis system that generates at least 300,24Nm^3 of hydrogen per hour. So, our best choice, is the Nel M Series Containerized PEM electrolyser.

Containerized PEM electrolyser "in situations where plant space is at a premium, costumers may want to site their electrolysers outside. At other times may want to configure an electrolyser for a more turnkey operation." [18] So, containerization is the best solution for easy outdoor installations. "The M series PEM Technology makes for a reliable and turnkey solution with minimal maintenance." [18]

On this series they have two models, the MC250 and MC500, that generates 246Nm^3/h and 492Nm^3/h respectively, so our choice goes to MC500 since we need at least 300,24Nm^3/h. We will present next the spec sheet from the product chosen:

MODEL	MC250	MC500
Class	1.25 MW	2.5 MW
Description	Fully-automated MW-class on-site hydrogen generator utilizing a modular containerized design for ease of installation and integration Tri-mode operation (selectable): • Command-following mode allows operation based on available input power • Load following mode automatically adjusts output to match demand • Tank filling mode operates with power-conservation mode during standby	
Electrolyte	Proton Exchange Membrane (PEM) – caustic-free	
HYDROGEN PRODUCTION		
Net production rate Nm^3/h @ 0° C, 1 bar SCF/h @ 70° F, 1 atm kg/24 h	246 Nm^3/h 9,352 SCF/h 531 kg/24 h	492 Nm^3/h 18,704 SCF/h 1,062 kg/24 h
Delivery pressure – nominal	30 barg (435 psig); full differential pressure H_2 over O_2	
Average power consumption at stack per volume of H_2 gas produced[1]	4.5 kWh/Nm^3	
Average power consumption at stack per mass of H_2 gas produced[1]	50.4 kWh/kg	
Purity (concentration of impurities)	99.95% [H_2O < 500 ppm, N_2 < 2 ppm, O_2 < 1 ppm, all others undetectable]	
Purity (concentration of impurities with optional high purity dryer)	ISO 14687:2019(E) Type I, Type II Grade D and SAE J-2719 Type I Grade L 99.9995% [H_2O < 5 ppm, N_2 < 2 ppm, O_2 < 1 ppm, all others undetectable]	
Start-up time (from off state)	< 5 min	
Ramp-up time (minimum to full load)	< 15 sec	
Ramp rate (% of full-scale)	≥ 15% per sec (power input mode)	
Production capacity dynamic range	10 to 100%	
DI WATER REQUIREMENT		
Consumption rate at maximum production	222 l/h (58 gal/h)	444 l/h (116 gal/h)
Temperature	5 to 40°C (41 to 104°F)	
Input water quality	Required: ASTM Type II Deionized Water, < 1 µS/cm (> 1 MΩ-cm) Preferred: ASTM Type I Deionized Water, < 0.1 µS/cm (> 10 MΩ-cm)	
Water purification system (included)	Reverse Osmosis/Electronic DI (RO/EDI)	
ELECTRICAL SPECIFICATIONS		
Electrical requirements	Typical installation: 6.6 to35 kV, three phase 50 Hz/60 Hz Low voltage, three phase required for balance of plant and ancillary equipment	
Power quality	Total harmonic distortion: < 5%, power factor: > 0.9 nominal power, at normal power	
PHYSICAL CHARACTERISTICS		
Electrolyser container[2] W x D x H	12.2 m x 2.5 m x 3 m (40 ft x 8 ft x 9.9 ft)	12.2 m x 2.5 m x 3 m (40 ft x 8 ft x 9.9 ft)
Rectifier/transformer container[2] W x D x H	6.1 m x 2.5 m x 2.6 m (20 ft x 8 ftx 8.5 ft)	12.2 m x 2.5 m x 3 m (40 ft x 8 ft x 9.9 ft)
ENVIRONMENTAL CONSIDERATIONS – DO NOT FREEZE		
Standard siting location	Outdoor, pad mounted Flatness 35/25 per ACI-117-10 Bottom access for AC and DC electrical connections, water and drains	
Storage/transport temperature	5 to 60°C (41 to 140°F)	
Ambient temperature	-20 to 40°C (-4 to 104°F)	
Altitude range-sea level	1,000 m (3,281 ft)	
OPTIONS		
• Medium voltage input 4.16 to 6.6 kV	• Thermal control unit	• High purity hydrogen dryer with dew point meter

Figure 17 - Nel PEM M series containerized spec sheet [18]

It relevant to mention that the model that was chosen is a 2.5MW class with a net production rate of 492Nm^3/h of hydrogen production. An important characteristic is the average power consumption at stack per mass of H2 gas produced of 50,4kWh per kg of hydrogen. Like we said before PEM technologies, have an excellent purity (99.95%), as also a fast start-up time from off state (<5min) and a ramp-up time (minimum to full load) less than 15 seconds. The water consumption rate at maximum production is 444 litres per hour.

3.6. PEM average power consumption

It was mentioned on the MC500 spec sheet that the average power consumption is 50,4kWh per kg of hydrogen. We also know that we need at least 27kg of hydrogen per hour for the mine. So, in a year, we will need about 236.520kg of hydrogen for heating, mining machines, transportation, cargo, and company vehicles. We can conclude that is expected that the power consumption from the electrolyser to produce the estimated hydrogen for the mine is around 11.920.608kWh, about 12GWh.

We have shown before that there are some renewable power sources near the Panasqueira mine. From the analysis, we might consider all the power generation estimated over one year, would be as follows, wind power 551.71GWh and hydropower 59.91GWh, a total of 611.62GWh, which means that the renewable available energy would represent only 1,96% of the energy required for the electrolyser produces the amount of hydrogen needed for one year (12GWh). So, if there is any chance to make an agreement with some of the companies that detain the exploration, it will be the ideal, true that some of the wind parks or hydroelectric power stations are not capable to provide all the power required. On the next table we will show the total power generated from each one, compared with the total power that will be needed for the electrolyser:

Table 6 - Total power generated from renewable power plants compared with power needed for electrolyser, per year

LOCATION	BARROCA	PAMPILHOSA DA SERRA	ALTO ARGANIL	CHIQUEIRO	GARDUNHA	TOUTIÇO	VIDUAL
TYPE	HYDRO	HYDRO	WIND	WIND	WIND	WIND	WIND
POWER GENERATED (GWh)	5,91	54	105	8,7	227	211	0,01
CAPABLE OR NOT	NOT	CAPABLE	CAPABLE	NOT	CAPABLE	CAPABLE	NOT
PERCENTAGE NEEDED	-	22,22%	11,43%	-	5,29%	5,69%	-

So, there are four possible scenarios to power up the PEM electrolyser:

(1) large hydropower from Pampilhosa da Serra, by using 22,22% of the total power.
(2) wind power generators from Alto Arganil, by using 11,43% of the total power.
(3) wind power generator from Gardunha, by using 5,29% of the total power.
(4) wind power generator from Toutiço, by using 5,69% of the total power.

Like mentioned before, the purpose is to identify the renewable energy that is needed to supply the electrolyser, which is 12GWh, to generate near 235.000kg of hydrogen per year. Idealistic speaking, looking for an arrangement with both companies that explore the mine and the power plant.

To produce 235.000kg of hydrogen per year, we will consume 2.115.000 litres of water, but we will also produce 1.880.000kg of oxygen that can be used to various purposes or even sold.

We need to analyse where to locate the electrolyser, nearby the water supply and build a specific line to transport the hydrogen to the mine or to transport the water to locate electrolyser nearby the mine. This cost analysis will not be made in this work but referred as relevant for further work.

3.7. PEM localization

Like we said before, the PEM hydrolysis technology it requires freshwater, purifying water. So, near the mine, we have a few solutions, like Zêzere River or Albufeira da Barragem de Santa Luzia. The best option, also because the water consumed by the electrolysis process, must be on a large area of water, so, the Albufeira da Barragem de Santa Luzia, located 10km on a straight line, is the best option.

Figure 18 - Localization of the PEM electrolyser

As mentioned before, we need to study the best location and means to transport the hydrogen produced on the electrolyser to the mine. From the possible solutions, we identified a dedicated pipeline structure from the electrolyser to the mine, locate the electrolyser nearby the mine and bring the water from the source or transported the hydrogen by trailers. We will come to the solution later in section 3.9, as well as the solutions to store the hydrogen and fuelling equipment.

3.8. Hydrogen fuelling equipment

Still choosing Nel has hydrogen equipment provider. Now we are studding the best way to storage and fuelling hydrogen.

First, we will present the H2Station from Nel, it is a hydrogen refuelling station “that enables a safe, effective, and fast fuelling of both 35 and 70MPa fuel cell electric vehicles” [18] with high capacity and efficiency, we understand that is a great choice to fuelling, for example, the company vehicles or the trucks. “H2Station is an all-integrated module that includes all equipment required for hydrogen fuelling being a compression capacity, cooling and the required control system.” [18] It has a flexible scaling of capacities to meet increasing demand with up to 500kg H2 per day for cars and 1500kg H2 per day for trucks, as also a multiple dispenser connection option. There are several models, but still the best option with CE approval & certification is the H2Station HS004, with a maximum capacity of 66kg per hour at 70MPa, have 2 dispenser connections one of each (70MPa and 35MPa) and a maximum operating pressure of 100MPa.

Figure 19 - Nel H2Station and hydrogen dispenser [18]

Next, we need to attach a hydrogen dispenser to Nel H2Station, Nel have a compact footprint solution and a simple user-friendly Hydrogen Dispenser for fuelling of both 35 and 70MPa vehicles. With a very high accuracy of dispensed mass measurement and an infrared communication system to secure a fast and safe fuelling of the vehicle. Nel have also several dispenser types, but the best CE approval & certification option is the Nel Dispenser 35 MPa EU, for 2 – 40kg or 10 – 50kg vehicle tank sizes. The tank sizes of 2 - 40kg, have a fuelling protocol SAE J2601-1/2 and a nozzle design model WEH TK17 35MPa. For vehicle tank size of 10 - 50kg with fuelling protocol SAE J2601-2, have a high flow nozzle model WEH TK16 35MPa.

3.9. Hydrogen storage and transport solutions

First, we are going to analysis the hydrogen transport options. There are two main methods to increase volumetric energy density, compression and liquification. We present on the next figure the main characteristics for both cases:

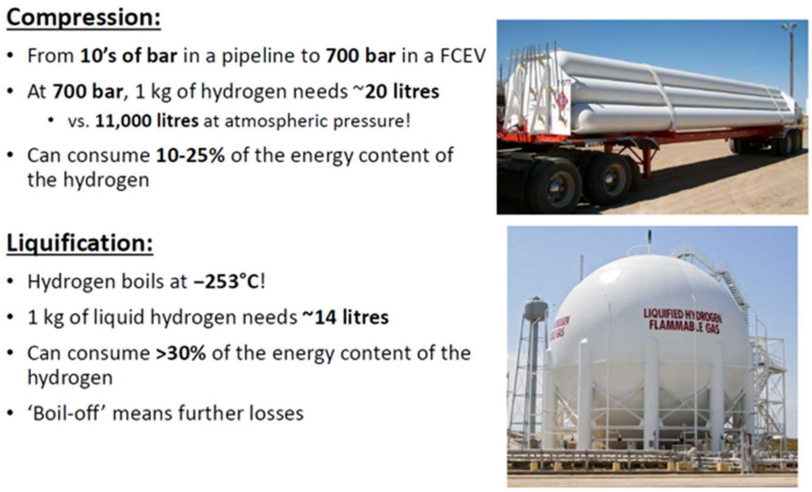

Figure 20 - Hydrogen transport options [14]

Next, we will present hydrogen storage solutions. Nel have the specific equipment, a safe medium to high pressure storage that ensures convenient and effective fuelling with a buffering capacity to meet the required capacities for a fast 70MPa fuelling of hydrogen at H2Station, additionally have flexible configurations of valve panels and storage vessels, that allows the Fuelling Storage to expand for the further demands in the future. The PED approval and certification model FS004 is the best solution for our case, with a maximum operating pressure of 50MPa and 100MPa. As safety solutions, has leak detection and jet fire protection and the valves have double block and blee.

Figure 21 - Nel Hydrogen fuelling storage [18]

4. Techno-economic analysis

Green hydrogen generation is becoming a sustainable strategy to global energy decarbonization and for future energy demands, however, these days, this path is way more expensive than other alternatives. Now, almost all hydrogen production comes from steam methane reforming (SMR), complemented by a relatively low price of €1 to €2 per kg. In the other hand, since green hydrogen uses renewable energy to power the water electrolysis system, his currently cost may vary from €3 to €8 per kg depending on the region, still, for a long-term solution to tackle decarbonisation and climate change is in fact, the best solution. The difference between green hydrogen costs is mainly affected by renewable energy production prices, countries where renewable energy price are lower, will also have a lower price on green hydrogen, but sill, over the year is expected that prices of renewable energy production will reduce, as also the initial investments requirements. We will present next a projection of green hydrogen cost all over the world:

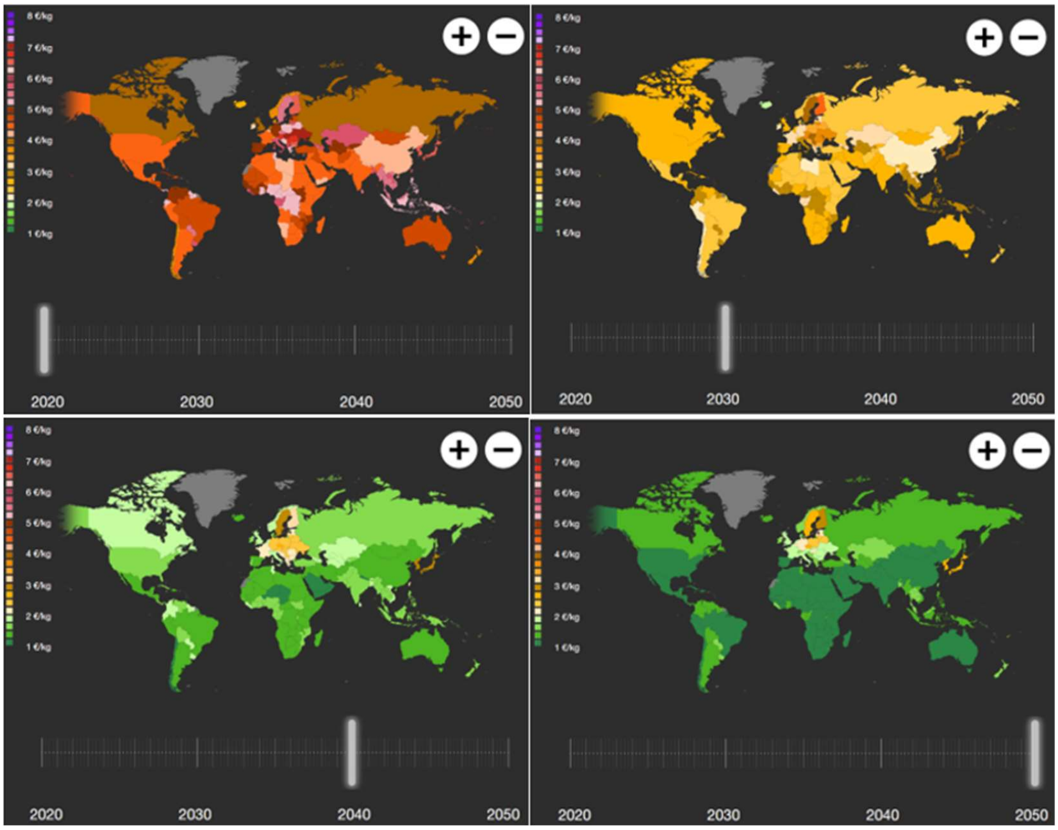

Figure 22 - PwC research | based on an analysis of various renewable energy sources and electricity generation / hydrogen equipment cost reductions worldwide [22]

The prediction on the renewable hydrogen production costs is to decrease over the next 30 years, motivated mostly by three factors, like Hydrogen Council presents on the Hydrogen Insights 2021 Report. First, “capex requirements are dropping” [15], second “the levelized cost of energy (LCOE) is declining” [15] and third “utilization levels continue to increase” [15]. We will present next a chart that shows the hydrogen production costs by production pathway:

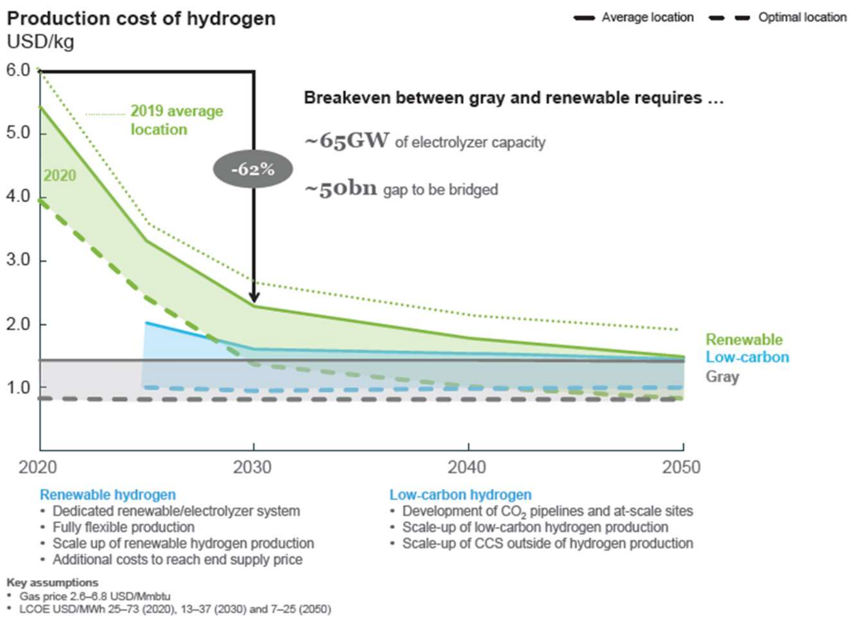

Figure 23 - Hydrogen production costs by production pathway [15]

“Including carbon costs for emissions related to gray and low-carbon hydrogen production greatly influences the breakeven dynamics between gray and renewable hydrogen” [15] as we present on the next chart:

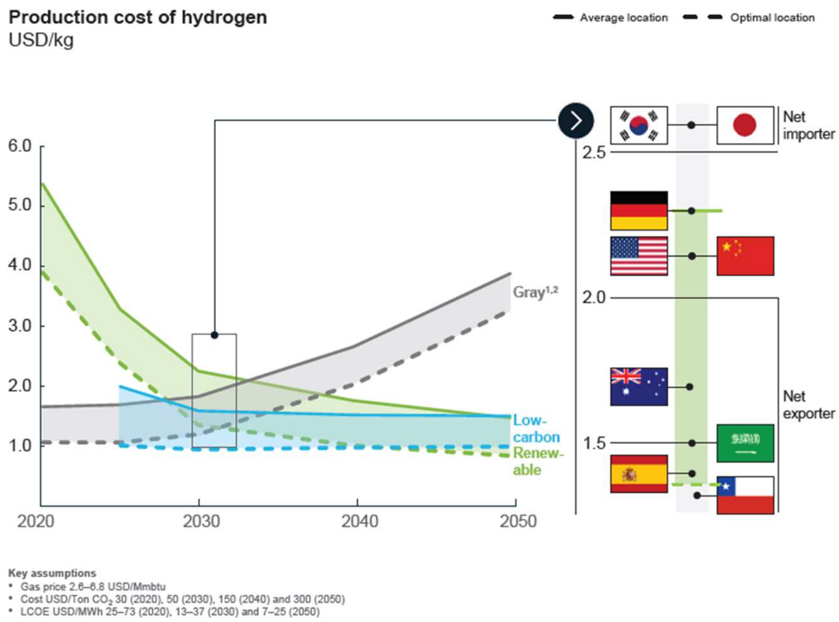

Figure 24 - Hydrogen production pathways, including carbon costs [15]

On our case of study, the Panasqueira Mines consumes around 115 tonnes of diesel for heating production and about 550 tonnes for transportation, on total of 665 tonnes of diesel consumption over the year. On the next chart we present the prices from diesel and heating diesel on the last 10 years:

Figure 25 - Diesel and heating diesel over the last 10 years [21]

It is also expected that over the next,10, 20 and 30 years, the prices will increase, nevertheless, we will assume that the prices of diesel and heating diesel will be similar all over the years, so, in the analysis that we will present next, this is a benefit for fossil fuel scenario. So, it is expected that the mine should spend around 105.000€ per year on heating diesel and 740.000€ on diesel, in a total of about 850.000€ per year on all diesel consumed.

On electricity consumption, it is expected that will be related over the next decades as we can see on the next chart:

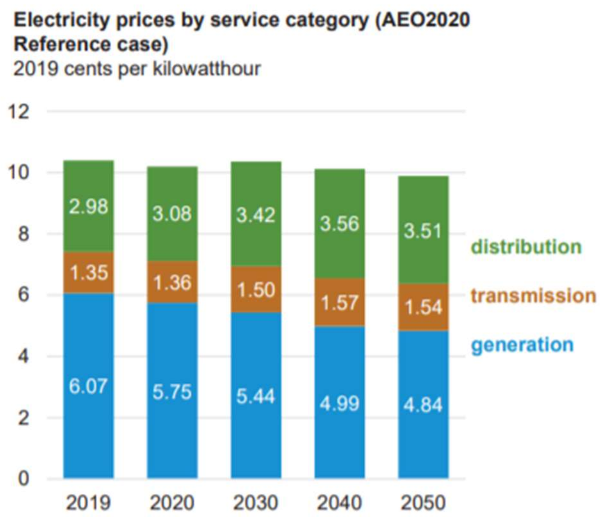

Figure 26 - Electricity projection over the next decades [7]

From the data provided by the mine, the average costs on electricity are 1.450.000€ per year. On electricity alternatives, we already expect that renewable energy provided from renewable sources like wind power or solar PV power plants will be a better economical solution.

Next, we will evaluate the carbon dioxide emissions released from the mine. The tCO2e emissions per year on the mine are nearly 9500 tonnes. As been already predicted, due to European Union's Green Deal and the Paris Agreement, the price of carbon will increase over the next decades, as we can see on the next chart:

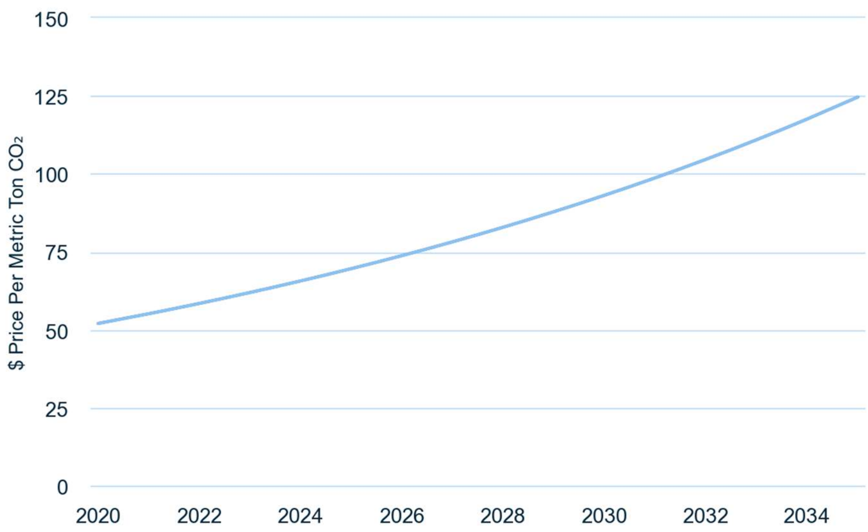

Figure 27 - Carbon price projection over the next years [23]

Currently, the carbon price per ton is 51,9€ [8] and the global mine emission per year are around 9.500 tonnes. So, we can estimate how much will be the costs from tCO2e emissions this year, about 495.000€. Since the projections of the carbon prince are predisposed to increase, for example in 2030, the estimated costs due to carbon emission, assuming 90€ per carbon ton, will be around 850.000€, almost twice as in the base line.

It is crucial to understand the pathway till green hydrogen becomes more viable than fossil fuel alternatives. We already know that hydrogen price now is approximately 5,4€ per kilogram, and by 2030 the hydrogen price projection is expected to be near 2.2€ per kilogram. On the mine requirement, we need 27kg of green hydrogen per day, in one year we will need around 235.000kg of hydrogen, about 1.270.000€ of hydrogen in 2021 and around 520.000€ in 2030. The next table will present several scenarios from these premises:

Table 7 - Mine costs comparation

YEAR	DIESEL + HEATING DIESEL	tCO2e	GREEN HYDROGEN	COSTS DIFFERENCE
2021	850 000 €	495 000 €	1 270 000 €	-75 000 €
DIESEL + tCO2e	1 345 000 €			
2025	850 000 €	665 000 €	820 000 €	-695 000 €
DIESEL + tCO2e	1 515 000 €			
2030	850 000 €	855 000 €	520 000 €	-1 185 000 €
DIESEL + tCO2e	1 705 000 €			
2035	850 000 €	1 200 000 €	470 000 €	-1 580 000 €
DIESEL + tCO2e	2 050 000 €			

On the table 7 we can find the mine energy related costs comparison for the next 15 years. For the analysis we will concentrate on the year 2030. From the data provided by the company that manages the mine, we know that annual consumption is 665 tonnes of diesel, considering the diesel price of 1,28€ per litre [21] as shown on figure 23, we can calculate that the mine spends about 850.000€ in 2030 on diesel consumption.

Like mentioned before, we did consider that diesel's price would not significantly change over the years. Using diesel as main source of energy, a great deal of carbon dioxide emissions will be released to the atmosphere. We also know that carbon price projection over the next years tend to increase as shown of figure 25. We know that the mine generates nearly 9.500 tonnes of CO2 per year, so from the chart presented on figure 25, where it is expected that carbon price will be near 90€ per metric ton of CO2 by 2030, from simple calculations the mine will spend 855.000€ due to these emissions.

In conclusion, it is expected by 2030 that the costs arising from the mine when using diesel are **1.705.000€** (850.000€ + 855.000€). If we use green hydrogen as an alternative for diesel, we may calculate as presented in chapter 3.4 that mine will need 236.520kg of hydrogen to replace diesel. From the chart presented on figure 21, in 2030 we estimate that hydrogen production cost will be around 2,20€, that means that mine costs for green hydrogen use will be **520.000€** in 2030. Looking at both cases, in 2030, the mining company will spend 1.705.000€ using diesel as energy source, including carbon costs, if they pick green hydrogen, they will spend only 520.000€, less **1.185.000€**. As shown on table 7, there is an increasing revenue that the company could justify and use to invest on green hydrogen as energy source.

Even today, with hydrogen production cost at 5,4€ per kilogram and the carbon price at 51,9€ per ton, green hydrogen is a viable solution although with relatively low revenue. To tone that we are using only OPEX costs into consideration, CAPEX costs were not considered as we could not reach the values for the machinery costs. Our objective is to understand where the break-even point is and to calculate the amount of profit that could be used to invest in capex. In 2035, profits almost double up comparing with 10 years earlier.

For this exercise we made some assumptions:

(1) The diesel price progression over the years was considered almost steady in conservative basis, as if we make this study considering the diesel price growth, like expected, the profit obtained on the further years would be higher.
(2) We were also conservative and considered that tCO2e prices growth over the next 15 years was nearly 2,5 times higher [23], with impact in the profit calculated.
(3) From what we can expect and from literature we considered green hydrogen production cost reduced by 2,7 times [15]. We are sure that the hydrogen will become more viable, sustainable, and efficient solution over the years if market takes off as foreseen in the EU Green Deal.

To make the green hydrogen more competitive, is vital that production costs drop, for that it is essential that the levelized costs of energy (LCOE in this case LCOH) decrease, and we can achieve this, mainly with the reduction of electrolyser capex (capital expenditure) as we can see on the following formula:

$$LCOH = \frac{\sum_{t=0}^{n}(Capital_t + vO\&M_t + fO\&M_t) \cdot (1+r)^{-t}}{\sum_{t=0}^{n} M_{H2} \cdot (1+r)^{-t}}$$

- $Capital_t$: total capital expenditures in year t
- $vO\&M_t$: variable operation and maintenance expenditures in year t
- $fO\&M_t$: fixed operation and maintenance expenditures in year t
- M_{H2} : annual hydrogen production in year t
- r : discount rate
- n : system lifetime

Other main reason to make hydrogen production cost decrease is the utilization levels to continue to increase, quoting the International Renewable Energy Agency (IRENA), "The higher the electrolyser load factor, the cheaper the cost of one unit of hydrogen, once fixed investments are diluted by a higher quantity of product output." [17]. "Electrolyser load factors should in general exceed 50% at today's investment cost levels, but nearly optimal hydrogen costs start being achieved at over 35%. This percentage will drop as electrolysers get cheaper." [17]. On the next chart we will present as example the levelized costs of hydrogen (LCOH) as a function of electrolyser load at grid connected Denmark:

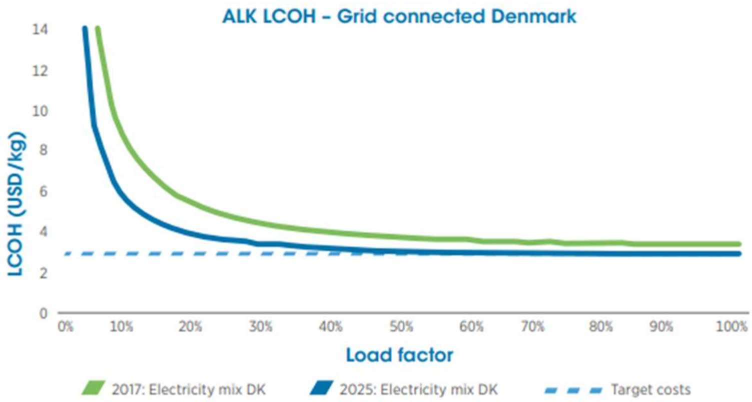

Figure 28 - Hydrogen supply cost as a function of electrolyser load [17]

To finish, we will present a chart where we demonstrate the influence of the levelized costs of energy (LCOE) and the electrolyser costs into the global hydrogen production cost with a load factor of 48%:

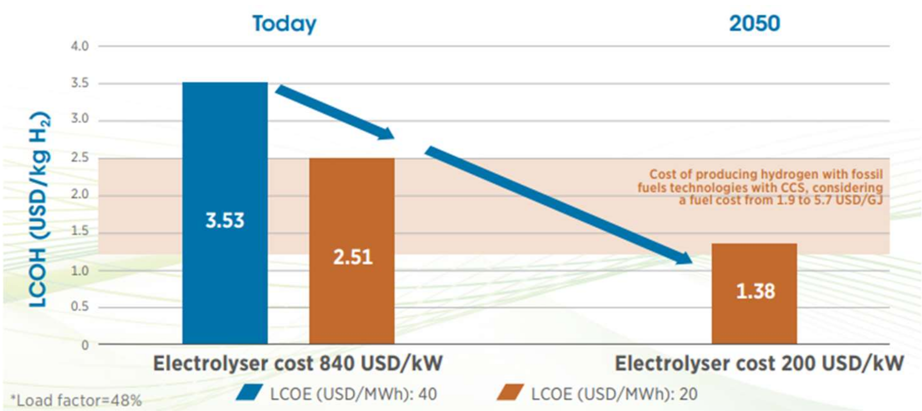

Figure 29 - Hydrogen costs at different electricity prices and electrolyser CAPEX* [17]

5. Conclusions

The main goal of this master thesis was to study the possibility of using hydrogen to decarbonize one case of the mining industry.

Hydrogen will be crucial to decarbonize sectors that are difficult to decarbonize just using renewable electricity. In this case the total mine energy consumption needs if supplied by fossil sources will generate almost 10.000 tonnes of carbon dioxide equivalent over one year. This situation suggests a deeper study towards an efficient and sustainable change.

The Panasqueira mine consumes almost 675 tons of oil equivalent for heating and transport uses, and with this study we intended to prove that green hydrogen would be the perfect solution to replace the energy source by a renewable one although at this moment the costs of production are higher that the existent solutions.

On electricity consumption, the mine has already viable solutions besides the use of the green hydrogen, wind or solar power plants can make electrification possible and viable, and most important, the prices from renewable energy sources will certainly decrease over the next decades as projections shows. There is already an ongoing project of a solar photovoltaic power plant for the mine energy consumption, it represents 20% of all energy that mine requires but it also represents an ongoing pathway for a renewable and sustainable system.

We studied different possibilities towards the implementation of H2 solutions. The possibility to develop an electrolyser system near the mine and technology providers either for the electrolyser and for the transport inside the mine. There are already around the world industrial suppliers and the market development will tend to lower the prices.

Green hydrogen production is becoming another sustainable strategy for global energy decarbonization when the decarbonization is not viable through the electrification.

For the upcoming years, even if the production cost is high now, in the coming years we will have more attractive prices, we are talking about almost 60% reduction on hydrogen production cost as we see on figure 21, and the expected growth on carbon emission prices, making the energy system totally or almost renewable.

We believe that green hydrogen will be a solution for Panasqueira mine decarbonization when compared to other alternatives, considering the amount of energy taken into account, as also the transport needs that are huge. Not even taking the capex costs in consideration, on the first year, green hydrogen seems to be a valuable solution. This is a process that could take several years, taking us to a moment that we will find more appealing prices on hydrogen production and investment costs. As on all technologies that are in the phase to reach maturity H2 projects need to be supported and promoted by using national incentives and supported by EU funds.

To finalize we must always be aware that in the EU Green Deal the priorities for the energy system are firstly to act at efficiency level and reduce consumption. Than to electrify the system using renewable sources and finally, when decarbonisation is difficult or to bring flexibility to the system through the energy system, we will use renewable gases where hydrogen is key. The digitalization of the system will contribute to optimize this energy mix.

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