Techno-economic assessment on hydrogen energy conversion systems for the Pulp and Paper and Metallurgical industries

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Abstract

Hydrogen, a very abundant element, has recently emerged as a relevant energy vector for the decarbonization of many sectors. Having a way to store energy locally, without the need to import fuel, seems a very appealing solution, especially for industrial processes that can not only benefit from the use of hydrogen, but also consume large amounts of highly pure oxygen, such as the pulp and paper and metallurgical industries. Advances and scalability of green hydrogen technologies are needed to achieve competitiveness with traditional methods, so this work proposes the identification of variables that influence its cost, as a substitute for natural gas. In this context, with the development of the green hydrogen economy, and based on the assumptions made in this work, it is shown that the substitution of natural gas, by hydrogen, is not yet competitive, considering the current prices. In the pulp industry, the electricity prices needed to achieve competitiveness with traditional production methods would have to range between 33-44 €/MWh, and for the steel industry, between 44-54 €/MWh, compared to the 90 €/MWh used as a reference. Under the same conditions, when considering the penalizing emission rates, these prices would have to increase to 236-265 €/tCO_2 for pulp and 189-281 €/tCO_2 for steel applications, compared to 60 €/tCO_2 today. These projects have the potential to achieve a LCOH of 1.56 €/t H_2, when storage and compression are not considered. If there is demand for O_2 in the value chain, part of this by-product can be consumed on-site with added value.
Keywords: Decarbonization; Hydrogen production; Paper and pulp; Steel; Energy and economic analysis

1. Introduction

Climate change and environmental degradation are, more than ever, a threat to our planet. In order to overcome these challenges, numerous proposals are being launched. In the light of the Paris Agreement of 2015, it is necessary to invest in the development of sustainable energy technologies in order to limit the temperature increase up to 2°C above pre-industrial levels while pursuing efforts to limit it even further to 1.5 ºC [11]. According to the Intergovernmental Panel on Climate Change (IPCC), if we wish to keep global warming below 1.5°C, the world will need be net zero by 2050 [16]. Failure to address the problem of greenhouse gas (GHG) emissions comprehensively, puts all generations, current and future, at risk.

The European Commission has since adopted the European Green Deal, establishing a strategic approach that places the energy and green transition at the centre of political action with the ultimate aim to reduce CO_2 emissions and transform the European Union (EU) into a modern, resource-efficient and competitive economy, where there are no net emissions of GHG, reaching carbon neutrality by 2050 [6].

Green hydrogen (H_2) emerges in this context as a possible solution to help achieve substantial reduction of emissions in these sectors. It is a non-polluting fuel gas (its combustion generates only water vapour) that can possibly replace the natural gas (NG) currently used in industry, decarbonizing the respective production processes. Moreover, it can be obtained through the electrolysis of water using renewable electricity in its production, functioning as an inexhaustible fuel. It is expected for H_2 to hold long-term promise applications in many sectors including transport, heating, power generation and energy-intensive industries, then forming a bridge between the power sector and industries where the direct use of electricity [4].

With the ambition for Portugal to achieve carbon neutrality in 2050, the National Energy and Climate Plan (PNEC 2030) was approved on 21 May 2020 [10]. Being of the main national focus to provide an integrated approach to profound decarbonization pathways for the energy system in Portugal, driven by a transformation of the industrial sector towards being sustainable, efficient, and a low-carbon economy, the present work seeks fulfillment of this objective and aims to explore the potential use of green H_2 together with highly pure oxygen (O_2) production through electrolysis, by studying the advantages of having a local energy source, with no need to import fuel, specially for industrial processes that not only can benefit from the use of H_2 but also consume large values of highly pure O_2. This study explores the potential in particular for the pulp and paper and metallurgical industrial sub-sectors and provides insights about the possible applications and benefits, both in economic and technical terms.

2. Background

2.1. Hydrogen Production

Water electrolysis based on electricity derived from renewable energy sources (RES) is the most environmentally friendly process to produce H_2, using the electricity to split water molecules into H_2 and O_2 as by-product [13].

In order to split the water molecule, the reaction has to be induced, which means that energy is required. An 100% efficient electrolyzer would consume around 33.3 kWh or 120 MJ to produce 1 kg of H_2 [19]. However, the inefficiencies of the used systems increase this value to ranges between 45-55 kWh/kgH_2 depending on the electrolyzer system efficiency. Approximately 9 kg of water are needed to produce 1 kg of H_2 and 8 kg of O_2 [19]. The main chemical reaction occurring is:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (1)$$

Three water electrolysis technologies are commercially available or under development: Alkaline Electrolysis (AEL), Proton Exchange Membrane Electrolysis (PEMEL), and Solid Oxide Electrolysis (SOEL).

AEL is a mature technology that has been undergoing research for decades and great progress has been achieved [19]. For this reason, AEL devices are the most commonly used H_2 generators in the industry industrial-scale applications [18]. It is formed by an anode and a cathode, which operates at with a liquid electrolyte solution (KOH/NaOH) with 25-30% concentration [26]. Anode and cathode are separated by a diaphragm or membrane with the dual purpose of carrying electric charge between the electrodes and separating the products formed at each electrode [18], which allows the flow of hydroxyl ions (OH^-) formed in the cathode to the anode, in order to obtain H_2 or O_2 at the cathode and anode respectively [18]. The process principle of an alkaline electrolyzer and the reactions occurring at each side of the cell are shown in Equation 2 and Equation 3.

$$Anode : 2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^- \quad (2)$$

$$Cathode : 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (3)$$

Cost reductions and technological improvements are expected due to large scale production [18], as shown in Table 2.1:

Table 1: AEL production pathways cost and properties projections [7]

AEL	Today	2030	2050	Unit
Efficiency	63-70	63-72	70-80	%
Stack Lifetime	50-90	73-100	100-150	thousand hours
CAPEX	450-1260	360-765	180-630	€/kW
OPEX	3	3	3	% of CAPEX

2.2. Oxygen as a by-product

As previously mentioned, 9 kg of water produce 1 kg of H_2 and 8 kg of O_2 at standard conditions of 25 °C and 1 atm [15]. This presents an opportunity to use this O_2 commercially by selling the by-product to the industries that inevitability need it, reducing the cost of H_2 production technology, thus helping to bring down the capital costs of electrolysis. Selling prices of O_2 are difficult to access and vary according to literature, depending on proprieties such as purity and final uses. The price range is between 0.85-1.10 €/kgO_2 in Portugal for medical purposes and 0.10-0.30 €/kgO_2 for industrial ones [3].

Oxy-fuel combustion is the process of burning fossil fuels with a pure O_2 gas mixture, totally replacing air as the source of oxidizer for combustion, increasing the O_2 content in boiler inlet from the 21% in plain air. Having only air in the combustion chamber boosts combustion efficiency [5]. In order to attain equivalent combustion properties, air-fuel combustion requires less dilution and more fuel [30]. As a result, oxy-fuel combustion has been widely regarded as a viable way to improve the performance of fossil fuel combustion processes while lowering pollution emissions, particularly CO_2. The U.S Department of Energy calculated the possible energy savings for commonly used process heating applications. The study suggests that when applying 100% O_2 instead of air, results in a 70% reduction in NG consumption [23] when temperatures are at 1650 °C. O_2-enhanced combustion is used primarily in the glass-melting industry, but other potential applications such as in the Pulp and Paper industry for lime kilns and black liquor boilers or in the steel industry for reheating, soaking pits, and reducing agents are possible [23].

2.3. Current state of the industry in Portugal

The energy dependence is a parameter that characterizes the extent to which an economy relies upon imports to meet its energy needs. The current value of the EU-27 is 60.6% and none of the countries have a negative energy dependence, which means that all depended on primary energy imports to satisfy their energetic needs [25]. Portugal had the eight highest energy dependence among EU-27. The national energy system will shift in a more pronounced way over the next decade, from an essentially fossil base to an essentially renewable base by 2050, with positive consequences in terms of reducing energy dependence, to reduce it to values of 65% in 2030 from the 74,2% in 2019 [10] [8].

According to a recent consumption forecast of April 2021 published by DGEG [9], the industry sector consumes the most NG (about 65%), mainly due to a lack of competitive clean alternatives. The price of fossil fuels is expected to remain relatively low for the next upcoming years. A carbon price would help to align the market return on clean-energy innovation with its social return by rising relative demand for clean energy sources.

CO_2 emission prices have expectations of a gradual increase over the next decade [24], and it is expected that in the next year prices could rise up to 100 €/tCO_2, specially after considering that this value have already reached 60 €/tCO_2 by September 2021, rising by approximately 50% since the beginning of the year [14]. This licensing costs, however, may have consequences in other not-so-predictable sectors. Electricity prices for the industry in Portugal have been fluctuating, with no declining or specific trend. This is believed to happen, in part, due to the fact that there is still a lot of electricity produced using fossil fuels that goes to the national grid, requiring a compensation for the emissions penalties in the overall price of electricity and. Moreover, investors' willingness to put money into growing supplies of a fossil fuel they believe that will be essentially outdated in 30 years has been stifled by the long-term goal of achieving net zero economies.

Pulp and Paper: Pulp mills could now be ideal sites for H_2 production as they have access to significant energy infrastructure with concentrated demand for a gaseous heating fuel and O_2. Moreover, in some cases, as renewable electricity at the pulp mill is already produced thought biomass power plants, meaning that the H_2 produced would already be a green fuel. If this H_2 is then burned in the lime kiln, even if only injected at a small percentage, the main source of fossil fuel based emissions at the pulp mill can be replaced. This would represent a significant decrease in the national NG consumption because this sector represents a great share of the yearly total consumption that has been increasing overtime.

Lime kilns are critical components of pulp and paper mills because they convert calcium carbonate ($CaCO_3$), a byproduct of the pulping process, to lime (CaO) [22]. To assist this reaction, the $CaCO_3$ must be heated to temperatures between 900-1000 °C in order to release CO_2 gas [22]. H_2 can substitute NG without significant modifications in the combustion equipment. At some pulp mills, H_2 has already been burned in lime kilns as a supplement to NG. For example, in the Stora Enso Oulu mill in Finland, 2000 tons of H_2 are utilized annually according to [22]. There has also been an increase in the O_2 demand in this sector in the recent years [21]. Lower production costs, greater paper quality, increased wood mass output, and environmental measures to eliminate chlorine compounds from pulp bleaching operations and replace them with environmentally friendly bleach solutions are the reasons for this. Therefore, this substance, is either produced at the mill or purchased and this means that having a suitably sized electrolysis plant, a separate O_2 production plant would not be need.

Metallurgical: Steel is typically produced in two stages: iron ore is first converted into iron and then, in a subsequent step, the iron is converted into steel. It can be produced using one of two methods: an integrated blast furnace (BF) with a basic O_2 furnace (BOF) process or through an electric arc furnace (EAF) [27]. The competitiveness of the BF-BOF process vs the EAF process varies by region, with factors like scrap supply and fuel costs having a big impact. Because the BF-BOF route accounts for 60% of European steel production [12], substantial emission reduction is only possible through the implementation of new breakthrough technologies [2]. EAF is heavily reliant on the availability of end-of-life steel, reason to support other advancements in steelmaking and not focusing only on EAF to address the decarbonization challenge [27]. It should be noted that when converting to EAF-based production, emission-free power will also play a significant role in the future.

There are a few options to decarbonize the process, including increasing the efficiency of current production methods, recycling steel, CCS and H_2. H_2 can be used in steel production in two ways: both as an auxiliary RA in the BF-BOF route (H_2-BF) or as the sole RA in the DRI process [12]. Oxy-fuel combustion technology has been widely regarded as a viable way to improve the performance of fossil fuel combustion processes while lowering pollution emissions, specially in high temperature intensive industry furnaces such as this one. Because a large amount of H_2 is required to be used as a RA, prolonged electrolysis of alkaline aqueous solution is required; this will be accompanied by a large amount of O_2 that can be integrated in an O_2 blast furnace (OBF), apart from being useful for industry and health purposes. Several options will be investigated in this work in order to provide different perspectives for the usage of these components in the steel industry's decabonization.

3. Implementation

In this section, different study cases will be developed for the application in the paper and pulp industry and for the metallurgical sector. The production of the chemicals will be onsite at the place of consumption in order to minimize transportation and infrastructure costs. The methodology used for the modelling of the study cases is based on different alternatives considered for the H_2 and O_2 production, conversion, utilization and prices. The goal of this study was to look at the technical potential and constraints of incorporating renewable fuel into the above listed sectors, as well as to determine the economic feasibility of the models that were chosen. The techno-economic implications were investigated by looking at the mass and energy balances.

3.1. Economic Characteristics and Assumptions

Only the initial investment is considered (electrolyzer) since no other acquisitions are expected to be accomplished (transmission systems, cables, compressors, storage, etc.). There is no requirement for storage if an electrolyzer operates as an online unit and produces H_2 or O_2 directly for use in the combustion processes. This simplifies and secures the process while also lowering the investment cost.

AEL is the most developed water electrolysis technology, and it is also the most used commercially available technology for an industrial-scale electrolysis process, therefore being the chosen method for this study. Table 2 presents the considered values for the baseline case. The project's lifetime was considered 10 years due to the annual operational days these industries have and the operational time the electrolyzer presents.

Table 2: Electrolyzer proprieties assumed for the base case scenarios [20]

	Current State	Unit
Stack Lifetime	84000	h
Efficiency	70	%
Input Power	47	kWh/kgH_2
CAPEX	900	€/kW

The methodology used to calculate the revenues coming from the gases sales/purchases considers fixed prices for O_2 and H_2 along the lifetime of the project. For the current study it is assumed on a first attempt that the produced O_2 in excess is not sold with medical purposes but to industrial ones, with a baseline case value of 0.2 €/kgO_2. Given the market's volatility and uncertainty, the value considered for Electricity and NG are the average of the prices practiced over the last 5 years for the collected data taken from [9]. Values considered for the baseline case are presented in Table 3.

Table 3: Economical values related to the gases and fuels production/consumption [6] [3]

Gases	Prices	
Industrial O_2	0.100 - 0.400	€/kg
Medical O_2	0.850 - 2.500	€/kg
NG	27.864	€/MWh
CO_2 emissions	60	€/tCO_2

3.2. Definition of Assessment Model - Pulp and Paper

CELBI was utilized as a model for the construction of this research case. With 350 operating days per year, CELBI's mill produces 800 kADt (AD - air dried) of eucalyptus pulp, which is equivalent to 2285.72 ADt/d. According to the assumptions, the amount of O_2 required for delignification and bleaching is 45.72 t/d. The heat demand of lime klin is met by 53.00 t/d of NG. Around 1.11 GWh/d of electricity is consumed, 393.95 MWh/d is excess produced electricity and, therefore, sold to the grid by the mill. Around 1.36 GWh/d of RE are produced at the local biomass plants. These values lead to a release of around 225.74 tCO_2/d.

Three cases of different configuration are studied in order to find out how electrolysis integration would affect the main mill mass and energy balances.

Pathway A: the electrolysis process is scaled to meet the O_2 demand for the different purposes of its application. H_2 is combusted in the lime kiln to replace as much fossil fuel as possible. To cover the O_2 demand, the required electrolysis power is 11.19 MW. In the case where the own electricity produced is consumed, this would mean that auxiliary systems would consume 68% of the excess electricity produced at the mill. H_2 production covers 30% of the fuel demand of the lime kiln with the production of 5.71 t/d of H_2, therefore decreasing the consumption of NG to 51.00 t/d.

Pathway B: the electrolysis process is scaled to meet the lime kiln fuel demand. The generated O_2 is firstly used to different purposes of its application and then sold to industrial facilities. To cover the total fuel demand, the required electrolysis power is 38.69 MW. In the case where the own electricity produced is consumed, this would mean that auxiliary systems would consume 100% of the excess electricity produced at the mill, therefore being necessary to use 39% of the electricity produced at the biomass power plant. H_2 production covers 100% of the fuel demand of the lime kiln. As a by product, 148.57 tO_2/d are produced, the 102.86 tO_2/d overproduced are sold to industrial facilities.

Pathway C: the electrolysis process is scaled to meet the O_2 demand for both the different purposes of its application and for boosting the combustion at the lime kiln with the O_2 enhanced combustion. A 25% decrease in the NG consumption is projected, as temperatures at the lime kiln usually are in the range of 950 °C [21]. To cover the total O_2 needs, the required electrolysis power is 24.18 MW. In the case where the own electricity produced is consumed, this would mean that auxiliary systems would consume 100% of the excess electricity produced at the mill, therefore being necessary to use 14.5% of the electricity produced at the biomass power plant. To burn the NG in an oxy-fuel combustion, 53.06 tO_2/d are needed to be injected, consequently decreasing by 25% the fuel demand of the lime kiln and the CO_2 emissions. As a by product, 12.35 tH_2/d are injected into the NG distribution pipelines.

General Assumptions: for the study case, the following assumptions have been made: the mill works 350 operating days per year; O_2 and H_2 produced have been considered pure; Labour costs are assumed to be the same; Feed water quality has been considered to meet the requirements for water quality with the type of electrolyzer; The feed water for electrolysis is assumed to come from the existing mill water treatment plant, and is not taken into account in the feasibility model; In the sample delignification process, the chosen O_2 charge is 16 kg/ADt, which corresponds to a typical charge [22]. In addition, oxidized white liquor is utilized at a rate of 2 kg/ADt. During bleaching 2 kg/ADt is assumed [22]. A total of 20kg/ADt; The value of realised emissions is adjusted to 4.25 kg_{CO_2}/kg_{NG} given the data; It is assumed in this study that the NG burners support all the injected H_2 without major investments.

For the economical assessment, it is assumed that the increase in the water need is insignificant as it represents for all scenarios less than 1% increase.

3.3. Definition of Assessment Model - Steel

A reference integrated steel plant assumed to produce crude steel, not based on a specific plant, was utilized as a model for the construction of this research case. The goal is to give a general picture of an European integrated steelmaking. As reference case, the most established route for steelmaking, the integrated route (BF-BOF), is selected. The evaluation is based on an average yearly production in Portugal of 30000 ton of hot metal with an annual operation of 350 days. careful look at cost estimates and emission reduction will be taken, for system-wide improvements to understand the competitiveness of an OBF, a H_2-BF and a H_2-DRI-EAF process, with a conventional BF and BF-BOF plant, as well as optimization possibilities and solutions.

Resource costs, have fluctuating market prices, as these resources are internationally traded commodities. The cost estimates for these materials are considered fixed given the lack of information regarding future prices and trends. In Table 3.3 the costs are presented, based on market prices from 2015-2018, reviewed by [28].

Table 4: Resources market prices [28]

Iron Ore (€/t)	Coke (€/t)	Coal (€/t)	PCI (€/t)	Lime (€/t)	Alloy (€/t)	Scrap (€/t)
120	300	200	177	100	1777	180

H_2-**BF**: The electrolysis process is scaled to meet the H_2 demand as a RA. The ratio is changes from 120.0 kg/tHM (HM - hot metal) of PCI to 27.5 kg/tHM [29]. This requirement results in an electrolyzer dimension of 4.62 MW (all electricity is acquired from the national grid and is considered to already be renewable) that produces 220 kgO_2/t_{HM}. For the development of the economical assessment, the O_2 market is explored, given the fact that a typical BF consumes 100 kgO_2/t_{HM}, leads to an over production of 120 kgO_2/t_{HM}. However, as mentioned, O_2 enrichment is necessary to maintain the thermal state of the furnace, adding 10 % of the O_2 produced to the BF for enrichment, and the remainder is sold. From the economic point of view, the most important results from technical modelling of H_2-BF process are: decrease in PCI consumption, increase in coke consumption (from 373.9 kg/tHM to 389.8 kg/tHM) and the decreased CO_2 emissions (from 1352.3 kg/tHM to 1063.2 kg/tHM) [29]. In this scenario, no initial investment is needed, apart from the electrolyzer to produce the needed H_2 and O_2.

H_2-**DRI-EAF**: Overall, because H_2 molecules are significantly smaller than CO molecules, H_2 molecules can penetrate much deeper into the iron oxide crystal structure, resulting in a higher degree of metallization [2]. The necessary H_2 ratio is 50 kgH_2/ts. The electrolysis process is scaled to meet this demand as a RA. This requirement results in an electrolyzer dimension of 8.39 MW that produces 400 kgO_2/ts. For the development of the economical assessment, the O_2 market explored, given the fact that only H_2 will be needed for the process itself, meaning that all O_2 is sold. From the economic point of view, the most important results from technical modelling of H_2-DRI-EAF process are: decreased iron ore consumption (300 kg/ts), increase in alloy consumption (11 kg/ts) and scrap (100 kg/ts), decrease in lime consumption (100 kg/ts), decreased fossil fuel consumption (18.1 GJ/ts) [2], increased electricity purchase (12.1 GJ/ts) [2] and decreased CO_2 emissions (1575 $kgCO_2$/ts) [17].

OBF: Changes in coke output consumption is the most significant impact of the OBF on BF raw materials. Because there are only slight variations in other materials, these are not included in the modeling as their consumption is not significantly modified. Changes in process gases streams also happen with the most significant being the increment of the mass flow of O_2 from 70 m^3/t_{HM} in the BF reference case to 220 m^3/t_{HM} in the OBF (100,03 kgO_2/t_{HM} to 314,38 kgO_2/t_{HM}). The avoided emissions when implemented a OBF with CCS is 975 kg/t of hot metal produced [1]. The electrolysis process is scaled to meet the OBF O_2 demand. This requirement for pure O_2 results in an electrolyzer dimension of 6.60 MW that produces 39.30 kgH_2/t_{HM}. This H_2 is sold to be injected in the NG distribution pipelines at the LCOH price. In these conditions, additional 3600 t NG are still consumed and purchased annually. From the economic point of view, the most important results from technical modelling of OBF process are: increased NG consumption (from 0.85 to 5.04 GJ/tHM) [1], decreased coke consumption (95 kg/tHM) [1], increased electricity purchase, decreased CO_2 emissions CO_2.

General Assumptions: For the study case, the following assumptions have have been made: the mill works 350 operating days per year; Only the major reactions of the process were addressed, and simplifications were made to keep the model basic, as it does not seek to go into detail of the chemical processes performed; All iron entering the EAF is considered to depart the process via the liquid steel product; Not all emissions from the integrated route are considered, only the most significant and direct ones; Labour costs are assumed to be the same; The coking plant remains as it is in the reference case; CO_2 is being separated from the recycle gas stream only for the operational requirements of the OBF, but there is no compression and transportation to permanent storage; No H_2 losses were considered; There is no electricity generation on the site; All electricity is acquired from the national grid and is considered to already be renewable, not taking into consideration transmission/cables investments.

3.4. Sensitive Analysis

The studied models are evaluated for specific industrial facilities, the physical and economic configuration of which were previously described. However, the goal of this study is not to provide the best solution for any individual situation, but to gain a set of insights that will assist decision makers. As a result, some of the variables that are identified to influence the final LCOH and NPV are investigated further by conducting a sensitivity analysis to determine their weight in the ultimate cost of H_2.

In attempt to predict how the future of H_2 would look, two alternative future scenarios are depicted, that lead to different sets of model assumptions. Considering that the life of the project is 10 years, the first scenario is a more conservative look based on the technology advancements expected for 2030, with no big breakthroughs, predicted by the various sources surveyed, where electricity prices are lower, emissions are already at 110 €/tCO_2 and the initial investment in electrolyzers has decrease approximately 33%. Scenario 2 corresponds to a more optimistic expectation, where the variables adopt values mentioned in the most optimistic cases of the above mentioned reports, where electricity prices are already at 30 €/MWh, emissions are already at 200 €/tCO_2 and the initial investment in electrolyzers has decrease approximately 80%. All variables are explored and changed in order to see the effects it has on the economical assessment. Hence, the included values in the analysis are as shown in Table 5:

Table 5: Variables included in the sensitivity analysis of Scenario 1 and Scenario 2

	Scenario 1	Scenario 2	Unit
CAPEX	600	200	€/kWe
LCOE	60	30	€/MWh
CO_2 cost	110	200	€/t
NG cost	36.000	58.896	€/MWh

4. Results and Discussion

After defining the various scenarios and parameters utilized in the calculations, the essential results are displayed below. The two industries produce similar results in some of the dependencies and parameters studied because the characteristics associated with H_2 production are similar, regardless of the nature of the purpose for which it is used.

4.1. Evaluation of Pathways

Calculations for the determination of LCOH are performed considering only the H_2 infrastructure. However, in order to improve the economics of the project, O_2 sales are considered in the NPV calculation. This value, for the current developments, would be of 4.88 €/kgH_2 on the production costs for all implementations. This was expected given the stated conditions of only considering the infrastructure required to produce H_2, excluding the O_2 sales. Therefore, it is concluded that a project of these characteristics has certain fixed costs that are very high. The achieved LCOH is in between the expected range of 2.5-5.5 €/kgH_2, according to the European Parliament's H_2-policy released on April 2021.

Once again, electricity consumption is highlighted, representing 87% of the total cost for. However, it is important to say that LCOH is not a fair comparison for these situations, because while Pathway A does not rely on any sales, the other scenarios do.

Pathway C presents a positive NPV with a PBP of 4 years and an IRR of 27.63%, however when selling the produced O_2 at a price of 0.6 €/kgO_2, this would allow the NPV to become positive for Pathway B with a PBP of 7 years and an IRR of 9.00%. For this particular case, adding the O_2 to the sales is determinant to make the NPV turn into positive and therefore making the project viable under the assumptions presented. Similar to what happened in the previous analysis, the OBF route appears to be the only profitable option to implement for the steel industry, with a PBP of 3 years and an IRR of 46.00%. However, selling O_2 at a price of 0.6 €/kgO_2, would allow the NPV to become positive for the H_2-BF with a PBP of 3 years and an IRR of 28.00%. Again, adding the O_2 to the sales is determinant to make the NPV turn into positive. However, it is unlikely that such a large quantity of O_2 could entirely be sold for that price, meaning that this would be a risky scenario for the current developments.

The feasibility of the case that aims to electrify the process and use H_2 to produce DRI is much more panning because, as notable in the the OPEX breakdown, costly additional electricity will have to be factored in. Even when the sub-product is sold at a higher price, this value remains negative, as opposed to the other scenarios considered, for which this price would make the projects competitive with the current methods.

4.2. Sensitive Analysis

Electrolyzer cost is the first tested variable in the sensitivity analysis. A reduction to the most optimistic value projected for the future price perspectives of 200 €/KWe is the limit of the reduction costs implemented, with the value being decreased by 100 €/KWe from the initial value of the baseline case of 900 €/KWe. This variation is linear and results in a cost reduction of around 10% of the LCOH for all pathways when decreasing from 900 to 200 €/KWe. This states the importance of electrolyzers as one of the main contributors to H_2 costs, however, it also evidences that electrolyzer cost reduction itself may not lead H_2 to a point where it is cost competitive with many applications. The LCOE is the largest contributor to LCOH, due to the high energy inputs required to produce H_2, therefore representing the main cost driver. In comparison, lowering the initial investment on the electrolyzer by 30% results in a 4% reduction in LCOH, while when lowering 30% of the LCOE, a 20% decrease in in the LCOH takes place.

The NPV of the Pathway C is already positive for the baseline conditions, so there is no interest in analysing this particular case. The influence of the emissions' price in the NPV is represented for all the other possible routes in Figure 1.

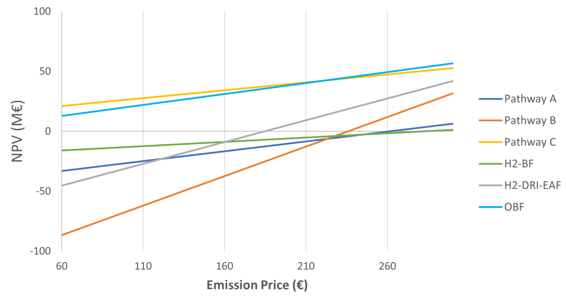

Figure 1: Price of Emissions influence on NPV.

After analysing the results, it is possible to understand that Pathway B is more sensitive (steeper slope of the line) to the increase of this value than Pathways A and C. This was expected, as Pathway B was designed to eliminate all CO_2 emissions whereas A only eliminates 33% and C has a decrease on emissions of 61%.

For the steel industry, H_2-DRI-EAF is more sensitive (steeper slope of the line) to the increase of this value than the other two routes because it was designed to eliminate much deeper the CO_2 emissions in the steelmaking process, whereas the other routes eliminate more moderately the emitted CO_2; the greater the sensitivity to this parameter, the greater the potential for decarbonization.

Table 4.2 sums up the emission levels at which the different routes would become viable:

Table 6: Emission price necessary to turn the project profitable for the current developments

	No Sales	O_2 =0.2€	O_2 = 0.3€	O_2 = 0.6€	Unit
Pathway A	265	-	-	-	€/tCO_2
Pathway B	328	236	190	-	€/tCO_2
H_2-BF	433	281	205	-	€/tCO_2
H_2-DRI-EAF	239	189	163	87	€/tCO_2

This analysis demonstrates once again two important factors, one being the already emphasized importance of the O_2 sales, and secondly how important these penalty fees will be to trigger investments in green technologies, as this price is set to increase widely due to the strong impact they have in the potential investments becoming cost effective over time. According to the trend lines, in a future when prices stabilize at higher values, forcing industries to participate in the transition, the higher the price, the more likely the routes with greater dedication to emitting less CO_2 will become the most viable option, as shown by the orange line versus the yellow and blue lines, and the grey versus the light blue and green lines with slower progressions. However, some of these values are quite high compared to the expectations of the EU policy, meaning that this indicator alone, will not be sufficient to trigger competitiveness in response to the conventional production method.

In Figure 2, the influence of the LCOE price (€/kWh) on the NPV is represented.

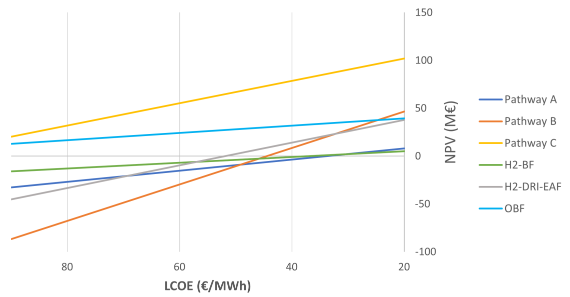

Figure 2: LCOE influence on NPV

Pathway C would rapidly become non-profitable with a small increase of 19 €/MWh and the OBF route would follow the same path with an increase of 30 €/MWh (at an initial price of 90 €/MWh). Pathway B, has a much higher dependence on the price of electricity than the other paths, with the orange line presenting a much steeper slope than the others. In the case of the steel industry, as expected, H_2-DRI-EAF has a significantly stronger dependency than the other options analyzed, because this pathway electrifies the entire production process rather than only using electricity to produce gases in the electrolyzer.

Table 7 summarizes the values for which the others routes would become competitive with the current methods when increasing the LCOE. Projects that are already competitive for current developments are assessed, as this value is unpredictable and could either increase or fall in the upcoming years. This analysis demonstrates how a small change in the cost of electricity consumption can significantly alter the profitability of a project with these characteristics. Electricity prices fluctuate widely, which can be problematic when considering implementing a system that is heavily reliant on the value of this input.

Table 7: Electricity price necessary to turn the project profitable for the current developments

	No Sales	O_2 =0.1€	O_2 = 0.3€	O_2 = 0.6€	Unit
Pathway A	33	-	-	-	€/MWh
Pathway B	10	44	56	91	€/MWh
Pathway C	108	-	-	-	€/MWh
H_2-BF	6	40	57	112	€/MWh
H_2-DRI-EAF	41	54	61	82	€/MWh
OBF	120	-	-	-	€/MWh

It is crucial to note that, under the reasonable assumption that O_2 may be supplied at a price of 0.2 €/kg, all options show values within the predicted range for a decrease in this price. This indicates that, once the increase of the penalty of the emission fee is also considered, these scenarios may become competitive sooner than anticipated.

Some of the conclusions reached in the scenarios' evaluation may be foreshadowed by the three above conducted analysis. Both Pathway A for the pulp and paper industry and the H_2-BF route for the steel research, in fact, turn out to be the one with the lowest initial investment, the lowest OPEX, and, while still non profitable, less harmful (NPV less negative) compared to Pathway B or the H_2-DRI-EAF. However, they also depict the slowest progression to both the emissions price and the LCOE, therefore less sensitivity, for these indicators, predicted to the most important strategies to battle emissions in the future. This means that these paths may not show much potential for future improvements.

4.3. Assessment of Scenarios

The weight of electricity is the same in all cases for being of 4.23 €/kgH_2 for the baseline case. When the price of electricity, efficiency, and initial investment of the electrolyzer are taken into account, this value can be used as a reference for any application that aims to produce H_2 on-site for its own consumption, without relying on other initial investments, should be able to use the value of 4.88 €/kgH_2 as reference.

For **Scenario 1**, these new LCOH are significantly lower than the baseline case, this value has a decrease of around 30% compared to the baseline case for all pathways, reaching a value of 3.26 €/kgH_2, allowing for the introduction of H_2 into newer and larger markets.

For **Scenario 2**, the calculated LCOH are 70% lower than the baseline. The utmost possibility, according to this study, is to attain a price of 1.56 €/kgH_2, which is within the range of the expectations on price drop for 2050. These low H_2 production costs allows to see where this technology can go in the medium term and long term for any application that aims to produce H_2 on-site for its own consumption, without relying on other initial investments related to compression and storage systems, reaching target costs and thus addressing these sectors sooner than than previously thought.

In fact, all projects in Scenario 2 are already competitive with the current methods. Pathway A the H_2-BF route, as predicted, turn out to be the least profitable for the future scenario due to the previously stated reasons. It is also worth noting that, in this study, the OBF route wind up exhibiting less appealing values than the baseline situation. This is because this approach still relies significantly on NG use and in the sales of the H_2 injected into the grid, which is now sold at a much lower price of 1.56 €/kgH_2 compared to 4.88 €/kgH_2 in the standard case. By that period, H_2 is already commercialized on a large scale, lowering its price, on which this model and Pathway C are heavily reliant. Pathway C, on the other hand, reduces NG consumption and by not consuming this fuel, compensates for the decrease in H_2 sales.

5. Conclusions

The most promising road forward for present advancements looks to be implementing oxy-fuel combustion in both industries. This path remains the most viable alternative until the price ranges of Scenario 1, with superior NPV forecasts. However, with lower LCOH and higher NG prices expected in the coming years, both scenarios suffer significant penalties, reflecting a less favourable investment over a 10-year time horizon. Scenario 2 uses the achieved developments to turn the baseline case's worst investments, the most desirable in both industries. These are the ones that have the greatest potential for CO_2 emission reduction. However, decarbonization of electricity production is a prerequisite for this.

Based on the values seen in the LCOE sensitive, for the pulp and paper the necessary values to achieve competitiveness range between 33-44 €/MWh and for the steel industry, these values range from 40-54 €/MWh, both when considering the standard O_2 price of 0.2 €/kgO_2. Under the same conditions, when considering the emission penalties, these range from 236-265 €/tCO_2 for the pulp and paper and 189-281 €/tCO_2 for the steel applications. These values are rather high in comparison to EU's policy expectations for the upcoming years, implying that this measure alone will not be sufficient to trigger competitiveness in response to traditional methods.

The economic viability of these H_2-based projects is thus largely reliant on the availability of low-cost clean electricity, higher carbon-emissions costs, with improvements in both areas required. Technological advancements in H_2 storage and electrolysis are critical to the process's competitiveness as these were not considered issues in the present work but can affect the LCOH considerably. However, it has been demonstrated that cost reductions in electrolyzers may not get H_2 to a position where it is cost competitive with many applications. These projects have the potential to attain an LCOH of 1.56 €/kgH_2.

This research showed that what appears to be a waste product, such as O_2, can considerably improve the project's economics and viability, improving the NPV by over 135 M€ (in the most optimistic case). If there is O_2 demand in the production value chain, some of this product can be used on-site; nevertheless, working with industrial gases providers will be crucial if this market is outside of these companies' scope.

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