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Green hydrogen, Bubble or energy reality?

Analysing the profitability of the sector

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September, 2023

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He began his professional career as an engineer responsible for hydrogen and renewable energy projects at the Aragon Hydrogen Foundation technology centre. Among others, he was responsible for design and construction,

of the hydrogen and electric drive system of the first 100% renewable sailboat to sail around the world in the Vendee Globe race.

In 2014 he co-founded Quionne, an engineering company in which he carried out projects involving hydrogen, electric mobility and carbon fibre parts, and his team was responsible for the electrical engineering of the first electric car to take part in the Dakar rally in 2015, a car originally designed as a hydrogen fuel cell vehicle.

In 2019 he co-founded EWM solutions (Energy and Waste Management) to bring innovative engineering solutions to the waste sector, from an energy perspective.

He is currently engaged in consultancy and execution of engineering projects related to hydrogen as an energy vector. He advises companies on their investments and projects, as well as technology centres based on his experience in fuel cell integration, hydrogen mobility, piping designs, sizing and planning.

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Index

Chapter 1

Current context

In recent years, hydrogen has gained prominence in the social, economic and energy spheres. This relevance is reflected in a continuous stream of news and announcements of large projects with investments at the same level.

And while this trend towards the development of green hydrogen exists, why is it that it has not yet become a reality and we do not see real projects springing up like mushrooms in our territories, and rather it seems that for the moment hydrogen is an expectation and project announcements, waiting to materialise.

This begs the question:

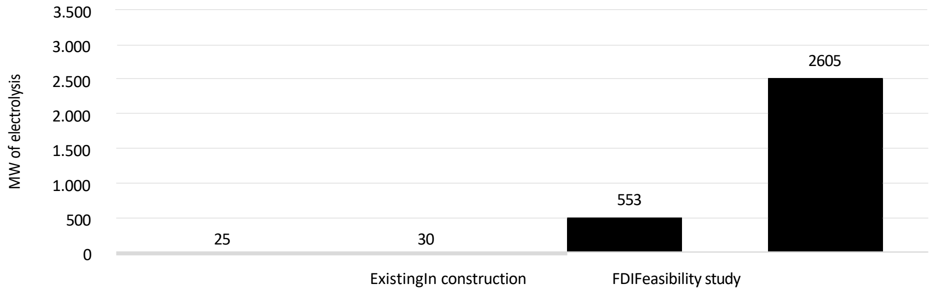
Will the high expectations of the hydrogen sector materialise?

And it is precisely to this question that we will try to shed light in this report. We will analyse what are the barriers and externalities on which the development of green hydrogen depends. Or rather, what are the barriers for each sector of green hydrogen; because hydrogen is just one gas, and the applications are so diverse that they require different sectoral analyses, as the barriers to overcome in each sector are different and so is the competition.

As we shall see, the profitability of the projects is the main aspect to be analysed in all cases.

Figure 01 → HYDROGEN PROJECTS ANNOUNCED IN SPAIN, WHERE IT CAN BE SEEN THAT THE VAST MAJORITY ARE IN THE FEASIBILITY STUDY PHASE.

Source: Real Instituto El Cano [1].



As explained in our previous 2022 report "Why hydrogen and why now?" [2], the main reason for the global push for renewable hydrogen is the need for an energy transition to non-CO2 emitting energy sources[2] . Taking into account that 80% of the world's energy consumption is not electricity, and that the main renewable energy sources generate only electricity (solar, wind, hydroelectric, etc.). This generates an imbalance between the consumption of electrical energy and fossil fuels, and therefore technologies are required to "electrify the economy", converting non-electricity end uses into electricity, either directly or indirectly, so that those end uses that are currently direct fossil fuel consumption (industrial heat, mobility, etc.) can opt to be supplied by renewable energies.

It is in this indirect electrifying function that electrolytic renewable hydrogen is positioned, as it is a combustible gas that can be generated from renewable electricity, and which does not emit CO_2 in its combustion (or oxidation in general). In this way, in absolute terms, hydrogen can decarbonise a large part of the 80% of consumption that is currently not electricity but direct consumption of fossil fuels.

At the same time, hydrogen is a combustible fluid (containing energy) just like fossil fuels, which is why it can perform similar functions to fossil fuels without emitting CO_2 . This enormous potential is what makes the expectations for hydrogen so high, with a target market of up to 80% of primary energy consumption.

However, as we will discuss throughout the report, the fact that hydrogen as a tool is capable of performing an action does not mean that it is the best option. Hydrogen as a tool could be likened to a multi-purpose knife, which serves many functions and is very versatile, but in many cases there are specific tools that perform each of the specific functions better. In this way, the hydrogen multi-purpose knife can be used for almost all the uses where fossil fuels are used today, but when we look at the markets, we will see that in many cases there are other alternatives or hydrogen is simply not competitive in that sector.

As the reader will already be aware, the message of this report is that the expectation created under the umbrella of hydrogen technologies is unlikely to be fulfilled, since it has been created with the superficial vision of being a "multi-purpose knife" that can be used for everything, but when the markets and real projects are unravelled, it is discovered that in many cases there are other "energy tools" that perform the specific function better.

And this is not to say that hydrogen has no role in an energy transition, but that it has very relevant specific roles, but probably not the generic role as a major transmitter of electrical energy to fossil fuels (80%) that has generated the current expectation.

As we will see, one of the main reasons why we have not yet seen the hydrogen economy take off is because all the proposed projects are still in the internal analysis phase. They are discovering the specific characteristics of hydrogen, its economic data, as well as its specific substitutes in each application. And that is why many projects are, not standing still, but investigating to find out whether hydrogen is the best option for their energy needs, or not, before investing.

At the same time, it is important to remember that in the world we live in, the market economy reigns supreme, far above environmental or sustainability/climate change values, and therefore the main competition for hydrogen is none other than the fossil fuels it is intended to replace. This is why in this report we will devote several sections to analysing how H_2 (hydrogen) competes with different fossil fuels in order to understand numerically how close or far hydrogen is from being competitive in terms of price.

To this end, we will analyse how the markets of the
3 main fossil fuels that represent 80% of the world's energy consumption (Oil, Natural Gas and Coal) and within the multiple uses of these fuels we will analyse in which ones hydrogen could be a substitute and what are the comparative economic data. So we will see at what price the fossil fuel to be substituted would have to be compared to the possible price of green hydrogen.

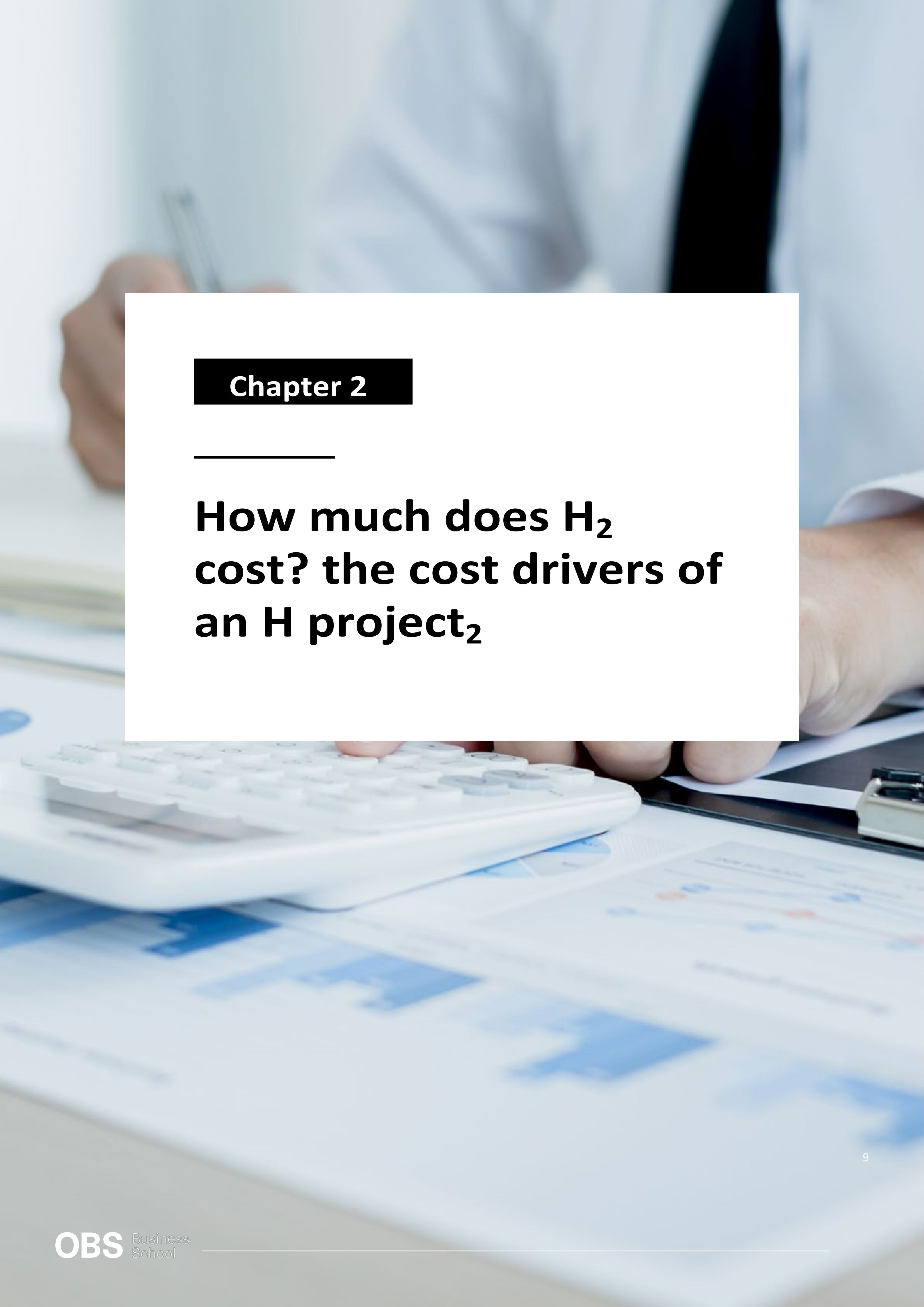
Throughout the report, we will compare the prices at which it is possible to generate green hydrogen with the prices that would make green hydrogen competitive in each market. Thus, if the price that makes green hydrogen competitive in each market is equal to or higher than the price at which it is possible to produce it, green hydrogen will be considered competitive in that market.

It is also worth noting that the expectation for green hydrogen was greatly reinforced by the high natural gas prices in the wake of the war in Ukraine, as, at those times of high prices, green hydrogen was a more cost-effective option than consuming natural gas, but those prices have moderated, and that moderation is also partly responsible for hydrogen projects moving at a slower and more reflexive pace.

We will carry out an in-depth analysis of what the cost drivers of green hydrogen are (how their cost is calculated and what it depends on) and how much they would have to improve to reach market parity with fossil fuels, depending on the prices of fossil fuels on the market.

We will also talk about the costs of CO emissions$_2$, which is a competitive advantage of green hydrogen over its fossil competitors, as it is a cost that green hydrogen should not have to pay and fossil fuels do. And that is why, even in purely market terms, an energy cost premium can be assumed when using green hydrogen instead of fossil fuels, as fossil fuel consumption, if not already in the medium term, will most likely have to pay for the CO emissions$_2$ that it generates.

We will also analyse how Europe (USA and other countries) are generating public funding programmes that seek to boost this "new" trend of green hydrogen as an energy vector that drives renewable energies. A good example of this funding is the Spanish PERTE ERHA, which seeks to invest 1555 million euros of European public money in the development of green hydrogen in the country [3]. And we will see how they are trying to promote it, analysing whether the economic flows are adequately oriented and whether they are sufficient to make renewable hydrogen competitive.



Chapter 2

How much does H_2 cost? the cost drivers of an H project$_2$

In this section we will try to shed light on the factors that come into play to determine the cost of green hydrogen, and in later sections, we will compare these costs with competing markets to better understand how close hydrogen is to being price competitive and on what factors its competitiveness will depend.

Throughout the report, we will compare the possible green hydrogen prices calculated in this section with those prices for which hydrogen would be competitive in each market.

Green, or renewable, hydrogen is a gas that is mainly produced by the process of electrolysis; a process by which electricity is injected into an electrolyser containing water inside it and with this energy the hydrogen and oxygen in the water is dissociated. In this process, hydrogen is obtained as a fuel gas, in which a large part of the energy provided by electricity resides, and oxygen is also obtained, which is a gas of lower economic value that is usually vented, although it could be valorised by improving the investment figures somewhat.

The main electrolysis technologies available on an industrial scale (greater than 1 megawatt, >1MW) in 2023 are PEM (Proton Exange Menbrane) and Alkaline, both of which have similar efficiencies of the order of 60% over the lower calorific value (LCV). This means that the electrical energy consumption to generate 1 kg of hydrogen is approximately 56 kWh/kg. Therefore, if the hydrogen when combusted, in its subsequent use, can provide 33.33 kWh/kg (LHV), this results in the above 60% efficiency (56/33.33). This is one of the most important parameters for calculating the price of hydrogen as the cost of energy is the parameter that weighs more heavily than the investment in the equipment. Efficiency means making better use of that energy cost and that is paramount.

In the future, SOE (Solid Oxide Electrolizer) technology is envisaged, which is expected to increase efficiency by an additional 10%, but is not yet available for large-scale industrial projects. AEM (Anion Exange Menbrane) electrolysers with lower costs are also envisaged in the future, but they are not yet available on an industrial scale, which is why in this report we will assume only PEM and Alkaline as available technologies.

Another factor to consider for the cost of hydrogen is how the efficiency of the electrolyser decreases over its lifetime, as the membrane loses capacity. This implies that, although the efficiency of the equipment is 60% at the beginning of its useful life, it will probably be 50% at the end of its useful life (typically 80,000 hours). For the time being, under optimistic assumptions we will assume that efficiency remains constant throughout the lifetime. However, it is important that electrolyser manufacturers start to guarantee these efficiency drops by contract as is done in the photovoltaic sector, as currently such "legal battles" are slowing down some projects.

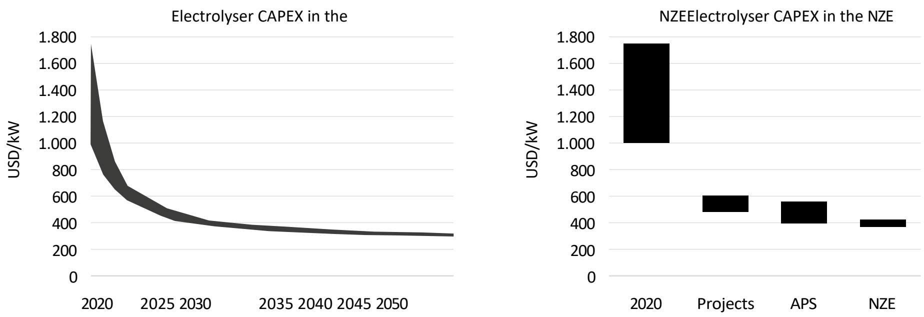
At the same time, it is worth asking about the durability of such equipment in order to better understand how long it will take to pay for itself and what the risk of the technology is. In this case, it should be noted that alkaline technology has a much longer operating history and is therefore a technology with a more proven durability. Although it is true that this durability is based on its old asbestos membranes, which were banned and the current membrane does not have that "track record" that guarantees real durability. PEM technology has much more limited operating histories that make the risk of compliance with the durability reported by the equipment manufacturer more questionable. In fact, this is another factor why projects are being delayed: the reluctance of manufacturers to ensure guaranteed operating hours (with penalties) or directly due to the implicit risk that investors see in the lack of previous relevant experience in equipment durability. In any case, the declared durability of both alkaline and PEM manufacturers is usually around 80,000 hours for the stack membrane, and a separate issue is whether they guarantee it or whether this figure is reliable based on experience.

Uncertainty in real durability and efficiency drops due to degradation is one of the current risks of electrolysis technology. The technology is seeking accelerated industrialisation, assuming risks that are greatly mitigated in industrialisation processes at a more measured pace, where the size of the installations is scaled up as relevant experience is gained, in years of operation, from installations that are immediately smaller in size. Electrolytic hydrogen is trying to run before it walks, going from installations of less than megawatts with a few years' experience to multi-megawatt investments with 20-year operations, and this involves a risk that someone has to assume.

It is true that the stack (the main component of the electrolyser), or rather the stack membrane, can be reconditioned once it has degraded or broken and this represents a reinvestment cost of between 30 or 40% of the initial CAPEX. Changing the membrane allows the rest of the investment in the electrolyser to be amortised over the 20-year life of the peripherals and pumps in the balance of plant (BOP). The BOP does have guarantees due to transfers from other sectors and because in Alcalino there is a history of many years of operation in multi-megawatt sizes.

Figure 02 → INTERNATIONAL ENERGY AGENCY PROJECTIONS ON INVESTMENT PRICES (CAPEX) FOR ELECTROLYSIS SYSTEMS

Source: International Energy Agency [4]



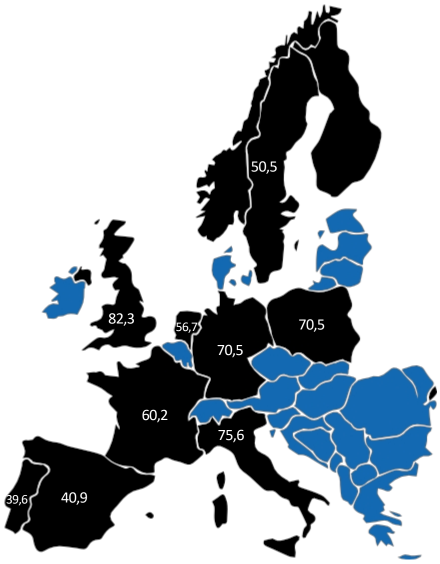
Once the efficiency and durability of the electrolyser has been defined, it is worth looking at the investment cost and how it is evolving. In general terms, it could be said that the investment cost of an electrolysis plant is between €750 and €1200 per kilowatt installed. Although the costs are expected to fall exponentially as the plants are installed, in the last year these costs have risen by as much as 20% in some cases. Figure 2 shows the price trend expected by the IEA (International Energy Agency).

Once the investment cost of the electrolyser, its durability and efficiency are known, the necessary parameter for estimating costs is the availability and price of green energy to be injected into it. In this case, two parameters should be differentiated: the average cost of energy in euros per megawatt (€/MWh) and the annual hours in which energy is available at that price and with guarantees of green origin.

The cost of renewable energy varies depending on the location of the plant, but for this case we will take Spain as an example. According to the report "PPA Times - May 2023 Edition", prepared by Pexapark [5], the price of a PPA (Power Purchase Agreement) in Spain would be 40.9 €/MWh. Figure 3 shows the average prices for the European reference countries. This PPA cost means that it is possible in Spain to sign a long-term green power exchange contract at this average price and is therefore the average price we will assume for our calculation. Although it is true that access tariffs and tolls should be added to this price, we estimate an average energy price for our financial model in Spain of 50 €/MWh. The evolution of these prices is expected to fall as more renewables are installed and there is more surplus electricity.

Figure 03 → AVERAGE COSTS OF RENEWABLE PPA IN SPAIN IN 2023, EXCLUDING TOLLS

Source: Pexapark [5].



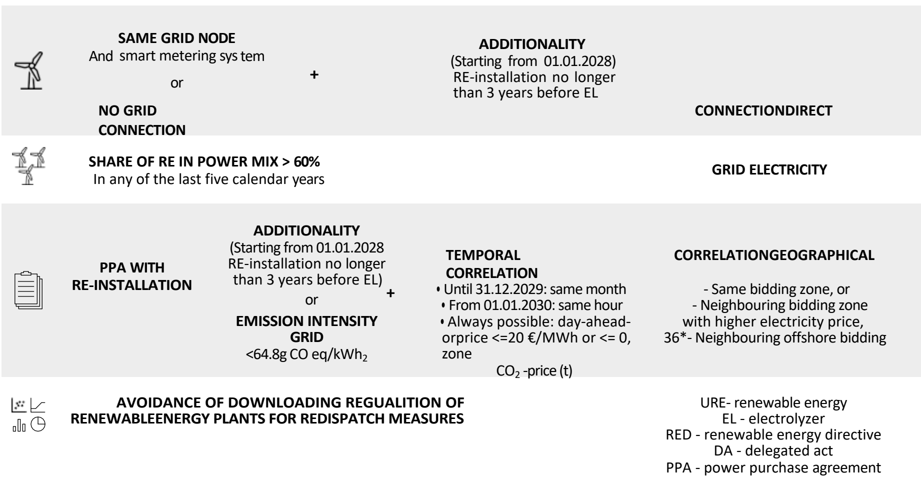
Finally, it would be worth reflecting on the annual hours in which this energy is available with green guarantees, at this defined price (50 €/MWh), and therefore the hours that we can operate and amortise the electrolyser per year. And this is a complex reflection, as the guarantees of origin depend on the regulations that dictate them, and in the European case these are the delegated acts of the European Commission (EC) referring to green hydrogen [6], which state that until 2030, monthly time correlation between electricity and hydrogen generation will be required, and from 2030 onwards, hourly time correlation will be required.

As H_2 projects are delayed in their installation and, moreover, are projects that, from engineering to start-up, will easily take two years on average, we could start to see the hydrogen projects announced today materialise in 2026. This factor, together with the fact that the useful life of these projects is 20 years, means that for most of their useful life these projects will be subject to time correlation (according to the EU delegated act [6]). And that is why in this analysis we will consider time correlation during the whole life of the project.

This means that from 2030 onwards, a kilowatt hour (kWh) generated by a renewable source will have to be consumed in the next hour by an electrolyser to be considered green hydrogen. What does this mean? Mainly that hydrogen cannot be produced at night with photovoltaic panels (quite consistently) and also not if there are no wind generators running and injecting the amount of energy needed at the time it is used.

Figure 04 → EXPLANATORY OUTLINE OF THE DELEGATED ACT IN RESPECT OF GREEN CERTIFICATES OF ORIGIN OF THE H_2

Source: FfE [7]



What does the hourly correlation imply in terms of equivalent electrolyser operating hours (load factor)?

- **In a photovoltaic or wind power plant without a grid connection point:** The equivalent hours will be equal to those of the renewable source (if there is no oversizing) and therefore in a photovoltaic plant connected to an electrolyser we cannot assume much more than 2100 hours per year and in a wind power plant 3000 hours per year.
- **In a renewable with a grid feed-in point:** If there is a sufficient grid feed-in point, the base load of the renewable can be used and the peaks can be fed into the grid. In this way, for example, a photovoltaic plant can be oversized to operate the electrolyser at full load from the first hours of sunrise and in the central hours discharge all the surplus energy to the grid. In these scenarios, up to 3000 hours/year could be achieved with a photovoltaic and perhaps close to 4000 hours/year with a wind turbine. Although these parameters would be highly dependent on the location and over-dimensioning.
- **In a mix of photovoltaic and wind with grid connection:** Finally, the most optimised option is to have a mix of photovoltaic, wind and grid connection in order to oversize them. In this way, whenever there is sun or wind, the electrolyser could be operated and also increase the hours given the possibility of over-dimensioning the sources and feeding the surplus into the grid. In these cases it would be possible to reach 5000 or even 5500 hours per year.

It should also be borne in mind that operating hours are sometimes offset by price, so that for example installations connected to photovoltaics directly have a lower cost of energy (without grid tolls) but a lower availability of energy in annual hours (2000h).

We have therefore concluded that a current green hydrogen production facility has approximately:

- An energy efficiency of 60% (over PCI, 56kWh/kg).
- Average stack life of 80,000 hours, BOP 20 years.
- The reinvestment of the stack is 40% of CAPEX.
- An investment cost of 0.75 to 1.2 €/W (installations >5MW).
- A usage factor varying between 2000 and 5500h.

Given these parameters, 3 approximate scenarios have been proposed to estimate a range of likely prices for renewable hydrogen projects in Spain, as shown in Figure 5:

Figure 05 →

FINANCIAL MODEL DEVELOPED BY THE AUTHOR ON THE BASIS OF THE PARAMETERS DEFINED FOR DEFINING A H_2 RENEWABLE PRICE RANGE

Source: Own elaboration

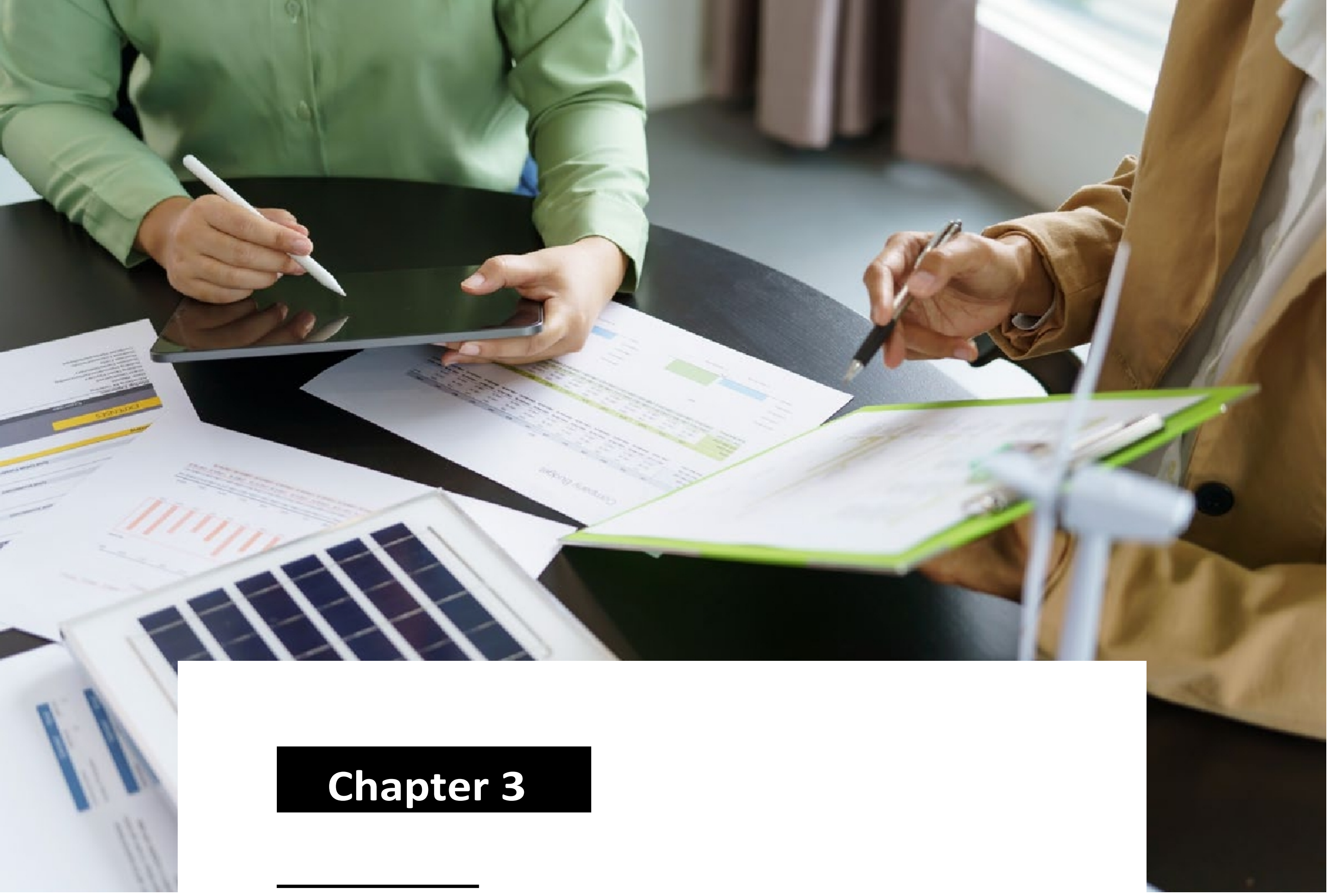
ESTIMATED GREEN HYDROGEN PRICES (RENEWABLE WIND + SOLAR)				
	Conservative	Likely	Optimistic	
SERVICE LIFE OF THE ELECTROLYSER	60.000	80.000	100.000	
Hours of operation per day	8	12	15	h/day
Annual Operating Hours	2920	4380	5475	h/year
Years of electrolyser operation (stack)	20,55	18,26	18,26	years
Efficiency Electrolyser	60%	60%	60%	eff
$_{H2}$ production from MW electric	18	18	18	$_{kg/H2}$ h
Annual $_{H2}$ production	53091	79636	99545	$_{kg/H2}$ Year
Cost of electricity	60	50	40	€/MW
Annual cost of electricity / per MW	175.200	219000	219000	€/year
Revenue per $_{H2}$ window	292000	294655	298636	€/year
Flow of each year	116800	75655	79636	€/year
CAPEX (electrolyzer)	1.200.000€	850.000€	750.000€	€/MW
Production cost $_{H2}$	5,5	3,7	3	€/kg $_{H2}$
Return on investment (IRR)	165	111	90	€/MW
	7,7%	7,7%	7,7%	

From the financial model presented, it can be deduced that the price range that makes it profitable to produce green hydrogen in multi-megawatt (>5MW) projects in Spain is approximately between 3 and 5.5 €/kg, which implies an energy cost of the gas (hydrogen) of between 90 and 165 €/MWh.

The calculations made in this report are contrasted in order of magnitude by Figure 13, which shows similar results from an external source.

It should be noted that, in a sensitivity analysis, the primary factor on which the price of H_2 depends in the financial model is the cost of energy, as the model is much less sensitive to the other parameters.

However, the parameters shown in this report are approximate and are intended to show the method of calculation and the factors involved, as well as an order of magnitude of prices and range, never an actual project price.



Chapter 3

Electricity market: injection pressure from the photovoltaic sector

- Electricity accounts for approximately 20% of primary consumption in a developed country at present, but if the plan to electrify the European economy as set out in the Net Zero targets [8] is achieved, electricity should rise to close to 100% of primary consumption. In this way, renewable energy sources (mainly solar and wind) could supply a significant part of primary energy consumption without emitting CO_2.

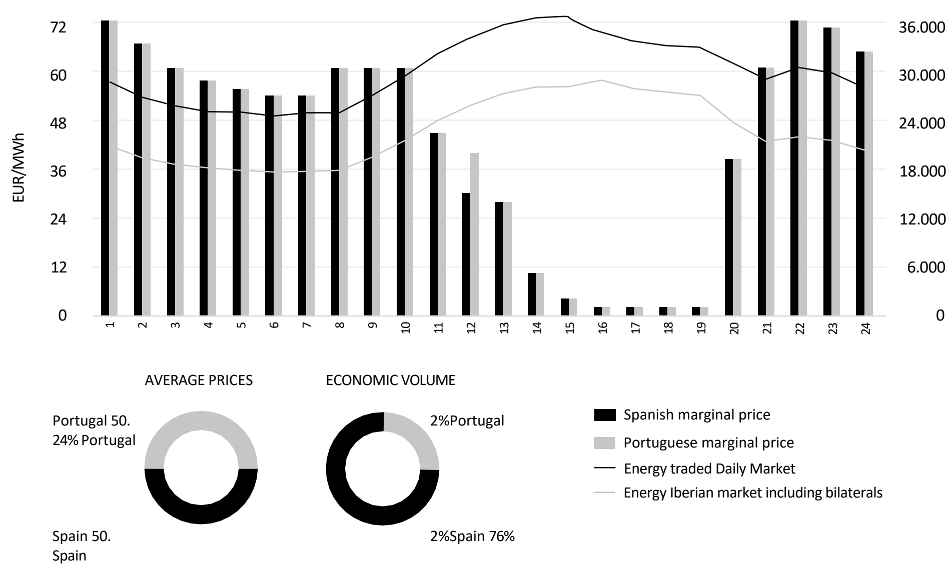
  This is the plan, the reality is much more complex, and the fact is that just achieving the current 20% of primary electricity consumption that is 100% renewable is a challenge; because renewable energies are intermittent (at night they do not generate the panels and if there is no wind, the wind turbines do not generate them) and the electricity grid requires energy and frequency stability. In other words, to get closer to the current grid being entirely renewable, energy regulation and storage systems would be needed to store energy when there is a surplus of renewables in order to be able to inject it into the grid when there is a shortage. And so an organised development of the grid could, perhaps, achieve a high insertion of renewables.

The problem is that development is not being organised and the promotion of storage systems and grid regulation is conspicuous by its absence. The result is that as renewables (especially photovoltaics) generate energy at very low costs (the lowest), photovoltaic parks are being installed on a massive scale until the grid is saturated. And this limit of grid saturation is beginning to be reached, as, in the absence of a sufficient storage system, there is a lot of renewable energy left over when the sun is shining and not enough when the sun is not shining. The photovoltaic sector is currently benefiting from the guarantee of supply generated by other technologies (fossil, nuclear, hydroelectric, etc.), and is forcing the system to saturation without paying for the effect it has on the grid. In other words, renewables have limitations in their access to the grid, which would be solved with storage, but nobody wants to pay for it, because it is more profitable to just install panels (there is no regulation for this either). Today, on many days, we can already observe how the price of electricity falls to zero due to the excess supply of renewables, in the so-called duck curve [9].

Figure 06 →

Source: Red Eléctrica [10].

EXAMPLE OF HOURLY PRICES OF THE SPANISH ELECTRICITY GRID ON 15 MAY 2021, WHERE IT CAN BE SEEN HOW THE PRICE FALLS TO ZERO DURING SOME OF THE SOLAR HOURS.



Hydrogen has sometimes been proposed to solve this problem, as a method of storing energy from the grid during times of renewable oversupply, and then converting that hydrogen back into electrical energy during times of renewable shortage. The problem is that the efficiency of the whole cycle (electricity-->electrolyser-->hydrogen storage$_2$ -->fuel cell-->electricity) has efficiencies of less than 25%. This means that 75% of the energy to be stored is lost along the way, which is why hydrogen should be discarded as a method of mass electrical storage.

However, investment in photovoltaics is so profitable that it has attracted a great deal of capital, especially to Spain, as it is the European country that offers the highest photovoltaic profitability [11] and these same capitals now see how the over-investment itself could go against them; as this over-investment (without control or network regulation measures) is generating the aforementioned zero electricity prices and in turn decreases in the prices of PPAs (Power Purchase Agreement, long-term energy exchange agreements). This means that their investments are at risk, as they assumed in the business plan revenues that are going to be reduced and profitability with them. Moreover, while this is happening with the investments already made, there could be a strong halt in the promotion of new installations, and if the old ones are not profitable, there is even less reason for the new ones to be profitable.

And this is where hydrogen comes in again, because photovoltaic investors, in their investment drive, want to continue with the photovoltaic business, but as the grid is saturated, they are thinking of generating hydrogen and selling it in other markets. And although the intention is along the right lines, hydrogen serves exactly that purpose, to displace fossil fuel consumption by generating it with renewable energies, the projects should be promoted from the other side, from the side of the fossil fuel consumers who want to decarbonise, as they are the ones who know the details of their consumption and particularities to be able to discern whether hydrogen is a good option or not for their application.

The problem is that these PV investors are used to selling electricity, a highly liquid and regulated market, and hydrogen is a diverse, complex market, in many applications still non-existent and captive where it exists. On the other hand, photovoltaic investment is simple and low risk, which is why many investors with little industrial qualification have been "encouraged" to invest, but hydrogen involves complex installations that currently offer little or no profitability.

For all these reasons, this investment drive is greatly inflating the "hype" for hydrogen, given the investment ambition of the photovoltaic companies; although these investors will have to convert a lot to invest in hydrogen, which is a chemical sector with much more engineering and risks. Moreover, these investors are used to high returns due to the transitory imbalance that has been generated in the electricity market, returns that are unlikely to occur in hydrogen in the short term.

This is one of the pressures that is forcing the hydrogen economy from hydrogen production without considering consumers, which together with public funding is driving projects where hydrogen is probably not, and will not be, the best option. This in turn is leading to many projects coming to a standstill because the profitability is not what is desired.

As we have emphasised since the beginning of the report, a hydrogen project has to work from the need of the final application (truck, ship, industrial...) and develop it from there to the production of the gas, and not the other way around. The first thing to check is whether hydrogen is a good option for the final application, long before even considering how or who is going to generate it.

The main reason for this section is to understand what forces are driving hydrogen to grow faster than is desirable for the order of the sector, as it is being driven by actors who have little understanding of the nature of hydrogen technology and are not taking the time to understand it.

Chapter 4

How much does the cost of emissions weigh on the price of hydrogen?

When we talk about market competition between hydrogen and the different fossil fuels, we cannot overlook the cost of emissions. Although most applications that burn fossil fuels are not subject to paying for the emissions they generate (mandatory market), the global trend is for more and more applications to have to pay for their emissions. This is therefore at least one factor to take into account when assessing hydrogen's competition with fossil fuels.

At the time of writing, the cost of CO emissions$_2$ is approximately €80/tonne emitted [12].

Figure 07 →

Source: Own elaboration

FINANCIAL MODEL DEVELOPED BY THE AUTHOR ON THE BASIS OF THE PARAMETERS DEFINED FOR DEFINING A
H_2 RENEWABLE PRICE RANGE

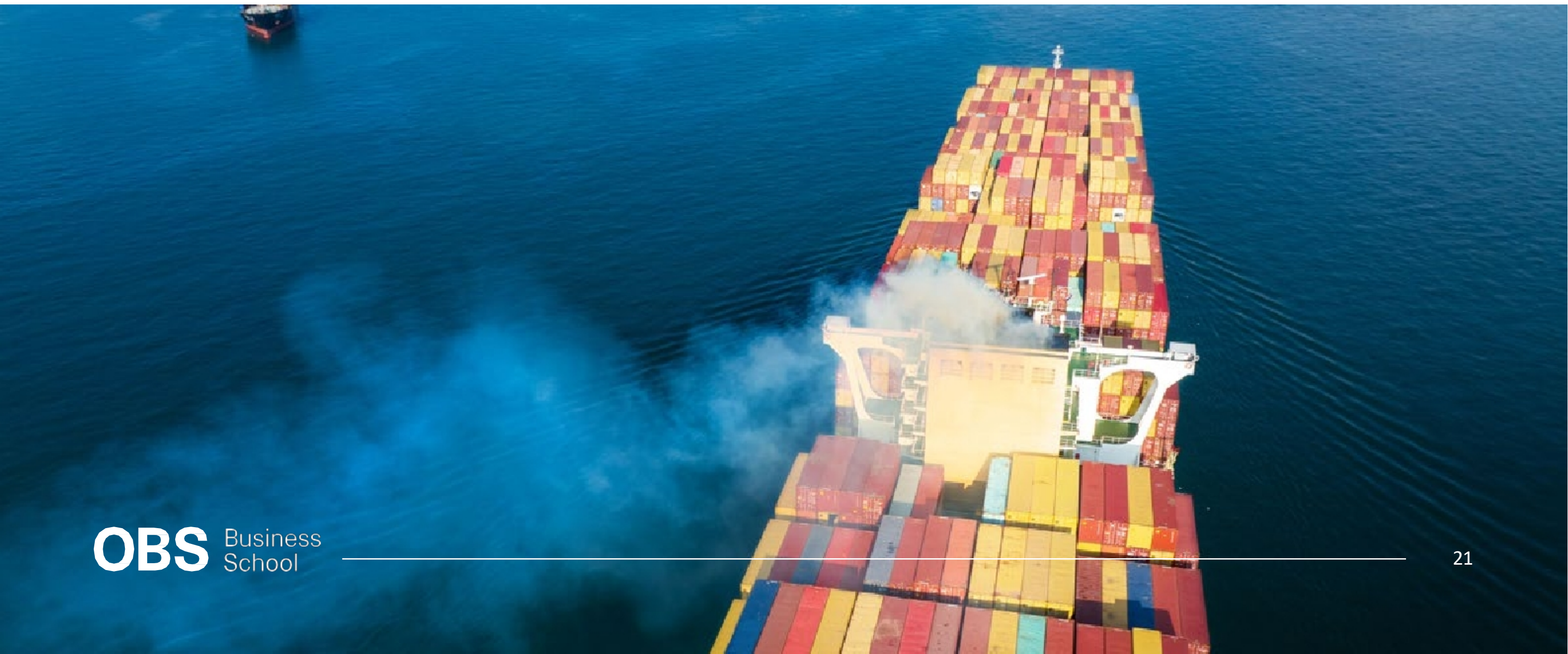
IMPACT OF EMISSIONS ON COMBUSTION VS. H_2

	Emissions Kg Co2/ MWh	Emissions cost €/MWh	Emissions cost with respect to combustion of $_{H2}$ €/kg $_{H2}$
Coal	400	32,0	1,1
Gasoil	275	22,0	0,7
Natural Gas	207,65	16,6	0,6

From the calculations in Figure 7 it can be seen that assuming a price of 80 €/tonne CO emissions$_2$, each MWh (thermal) of coal costs 32
22 for diesel and 16.6 for natural gas. This means that in an application that we replace with hydrogen we would be saving these amounts in euros for each MWh of heat generated and therefore it can be assumed that the extra cost per MWh of hydrogen would still be at market parity.

Expressed differently, for every kg of hydrogen burned we would be saving €1.1/kg H_2 in emissions costs, if the hydrogen is replacing coal in the application, €0.7/kg H_2 if it is replacing diesel and ��0.6/kg H if it is replacing diesel and €0.6/kg H if it is replacing diesel and €0.7/kg H if it is replacing diesel and €0.6/kg H if it is replacing diesel.
€/kg H_2 if replacing natural gas.

We will use these benchmarks for comparison in other sections.



Chapter 5

Competition with natural gas

Natural gas is one of the main fuels used by mankind today; in countries such as Spain it represents 21% of primary energy consumption [13]. Its main end uses are: heat generation (both residential and industrial) and electricity generation. In addition, natural gas is used as a chemical input for the generation of grey hydrogen through the reforming process. This grey hydrogen emits CO_2 in the generation process and is typically used to produce ammonia in the fertiliser industry, methanol for the chemical industry and hydrogenation of fossil fuels.

Green hydrogen as a substitute for natural gas has its clearest use in the substitution of grey hydrogen itself, displacing natural gas as the primary source of that hydrogen. Moreover, in this case, there is no other energy possibility, as such processes need hydrogen specifically, not an energy supply. The competition of green hydrogen with grey hydrogen will be discussed in Section 5.2.

On the other hand, hydrogen as a fuel gas can replace natural gas directly in its traditional uses of heat generation. The idea of direct substitution of natural gas by hydrogen gives rise to the phenomenon of blending (mixing and burning natural gas and hydrogen together). This phenomenon and the competition of natural gas with hydrogen as a fuel will be studied in section 5.1.

Figure 08 → DISTRIBUTION OF PRIMARY ENERGY IN SPAIN, BY FUEL TYPE

Source: Statista [14]

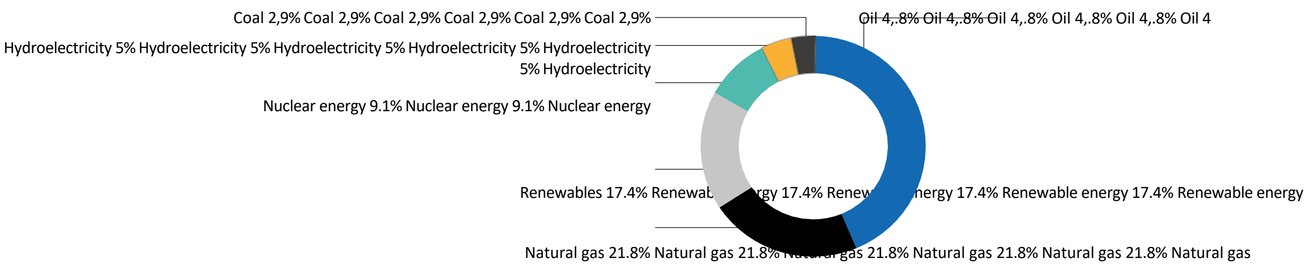
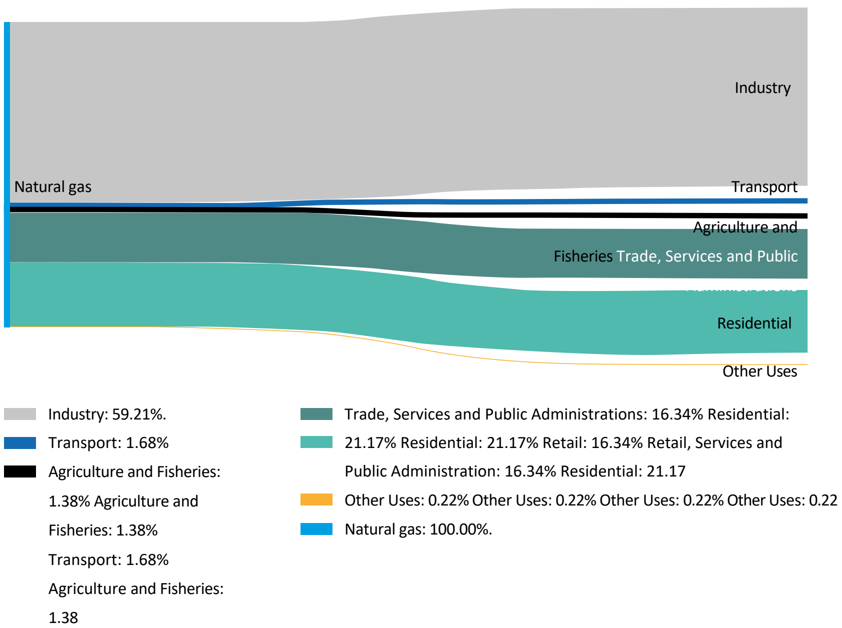


Figure 09 → NATURAL GAS CONSUMPTION BY SECTOR IN SPAIN

Source: Fundación Renovables [15].



5.1 Blending as a replication of the electric model

Blending is the process by which hydrogen is mixed with natural gas to be used interchangeably, mainly in burners to generate heat. It is an initiative strongly promoted by the gas lobby, as they are trying to reuse the existing network of gas pipelines they have in the territory, partially and progressively replacing natural gas with hydrogen [16].

Moreover, it is a model that the renewable sector (photovoltaic and wind) likes because, as explained in section 3, the electricity grid is beginning to be saturated with photovoltaic during sunshine hours. And the renewable sector sees the gas grid as an equivalent to the electricity grid into which it can pour its energy in the same way as it currently does into the electricity grid. In this case, the model would be to install photovoltaic or wind farms that produce hydrogen and inject it into the natural gas grid. This would replicate the liquid electricity market model in the gas market, using hydrogen as a vector.

The problem is that heat generation is a low value-added energy consumption in which a gas generated from electricity, the highest value-added energy, can hardly compete. This is the main reason why hydrogen combustion, alone or mixed, is progressing very slowly.

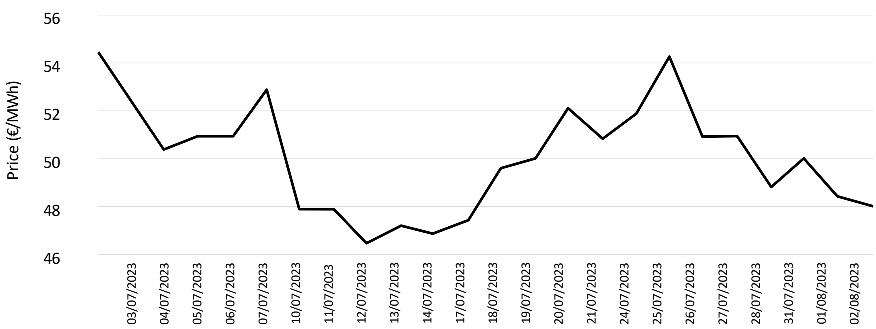
But, let's look at the numbers: The price of natural gas has fluctuated greatly in Europe in recent years as can be seen in Figure 10, with peaks of up to 300 €/MWh when typical values before the pandemic were 20 €/MWh. Currently in Spain, gas futures for 2024 are around 40-50 €/MWh as can be seen in Figure 11.

Figure 10 → NATURAL GAS PRICE VARIATION IN EUROPE FROM 2020, €/MWH

Source: ICE [17]

Figure 11 → CURRENT NATURAL GAS FUTURES IN SPAIN FOR 2024

Source: MIBGAS [18]



For the analysis of direct combustion competition (blending) we will to consider a range of natural gas prices from €25/MWh pre-pandemic to the €200/MWh that could occur at some future (extreme) peak. We will compare this data with the equivalent price that green hydrogen would have to pay to provide the same energy, taking into account that green hydrogen would not have to pay the CO emissions$_2$ defined in section 4.

Figure 12 → HYDROGEN PRICES TO BE COMPETITIVE WITH NATURAL GAS IN DIRECT COMBUSTION

Source: Own elaboration

	PARITY G	**AS NATURAL HYDR**	**ORGAN**		
		News			
Natural gas price	25	50	100	200	€/MWh
Emissions cost	16,6	16,6	16,6	16,6	€/MWh
Competitive price H_2 green	1,4	2,2	3,9	7,2	€/kg
Cost of production H_2 (Paragraph 4)	3 a 5,5	3 a 5,5	3 a 5,5	4 a 5,5	€/kg

As can be seen in Figure 12, for the expected price of natural gas in 2024 (50 €/MWh) and taking into account that hydrogen should not pay CO emissions$_2$ (which gives it a cost advantage) green hydrogen should have a cost of 2.2 €/kg to be competitive.

As we have seen in section 2, in the most optimistic (unrealistic) scenarios, the cost of producing green hydrogen would be at least 3 €/kg and probably €4/kg or more for most projects. And this is therefore the main reason why direct combustion hydrogen or blending projects are currently not profitable and development is slow or stalled pending public subsidies. The price of gas is simply too low for green hydrogen to compete in direct combustion.

We would have to see natural gas prices above €100/MWh again in the short term for hydrogen to be competitive, as these prices would make hydrogen competitive at €3.9/kg.

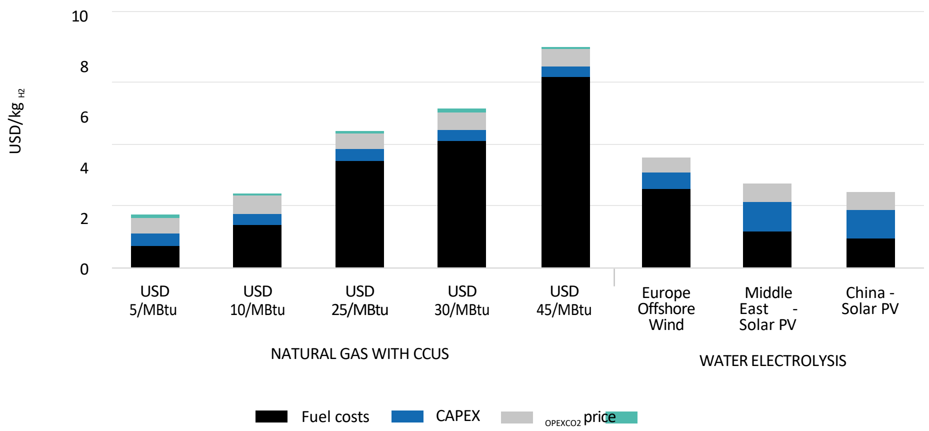
It is difficult for hydrogen combustion to be competitive with natural gas combustion in the medium term, and in many cases there are alternative technologies to gas combustion for generating heat, such as direct electrification or heat pumps, which are more efficient and profitable. In order to become profitable, sustained increases of more than 50% in the price of gas would be necessary, together with increases of more than 100% in the price of CO_2 , scenarios that are unlikely in the author's opinion.

The future of heat generation will be more about direct electrification (resistance heaters, electric boilers, plasma), solar thermal and heat pumps where the flow temperature is low, hydrogen will probably be relegated to specific niches where the required temperature is very high, but probably in the short term there will be no mass consumption and injection into the gas grid.

Figure 13 →

Source: EA, "Global Hydrogen Review 2022" [19].

ESTIMATED PRICES OF HYDROGEN PRODUCTION BY NATURAL GAS WITH CO_2 CAPTURE AND BY ELECTROLYSIS OF RENEWABLE ENERGIES. WHERE IT CAN BE SEEN THAT THEY ESTIMATE GREEN HYDROGEN PRICES BETWEEN 3 AND 4.5 USD/KG (3.75 MBTU IS APPROXIMATELY 1MWH, SO 10MBTU WILL BE 37.5USD/MWH).



5.2 Competition with grey hydrogen

As we have already explained, natural gas is also used today to generate hydrogen by reforming, to be used in the chemical industry, which needs the molecule to combine it with others, not as an energy input, but as a chemical input. In these cases, the only possible option for decarbonisation is to generate hydrogen with another non-CO2 emitting technology$_2$, i.e. green (or blue) hydrogen. However, since a reformer with an efficiency of 70% must be used to generate grey hydrogen, the competitiveness of green hydrogen is improved in this case compared to the direct competition in natural gas combustion as in section 5.1.

In this case we have taken the same range of potential natural gas prices 25 to 200 €/MWh as in section 5.1 (taking the most likely price for 2024 as 50 €/MWh). The result, taking into account the savings in CO emission costs$_2$, is that green hydrogen would have to cost 2.9 €/kg to be competitive with grey hydrogen today. This is very close to the most optimistic possible green hydrogen price estimates calculated in section 2 of €3/kg. However, the most likely price of green hydrogen in large projects would be €4/kg and therefore still some way from profitability.

Figure 14 →

Source: Own elaboration

PRICE CALCULATIONS OF GREEN HYDROGEN NEEDED TO COMPETE IN THE MARKET WITH GREY HYDROGEN

PARITY BETWEEN $_{H2}$ GREY AND $_{H2}$ GREEN					
		News			
Natural gas price	25	50	100	200	€/MWh
eff refurbished (approx)	70%	70%	70%	70%	
Price H_2 grey	35,7	71,4	142,9	285,7	€/MWh
Emissions cost	16,6	16,6	16,6	16,6	€/MWh
Price eq H_2 (green)	52,3	88,0	159,5	302,3	€/MWh
Competitive price H_2 green	1,7	2,9	5,3	10,1	€/kg
Cost of production H_2 (Paragraph 4)	3 a 5,5	3 a 5,5	3 a 5,5	3 a 5,5	€/kg

The profitability of green and grey hydrogen is close. With slight increases in the estimated price of natural gas in 2024 plus CO costs$_2$ together with investment subsidies for electrolysers, these types of projects could begin to be installed in the coming years. In addition, it should be noted that in these cases green hydrogen is the only decarbonisation option, so the public subsidy drive in this case is being stronger.

Green hydrogen as a chemical input replacing grey hydrogen is the strongest and most profitable bet in the whole green hydrogen universe. They will certainly be the first large-scale projects to come on stream. In fact, there are already examples in Spain, such as the 20MW electrolysis plant that Iberdrola already has in operation in Puertollano to produce ammonia for Fertiberia [20].

Chapter 6

Competition with oil

Oil consumption in countries such as Spain accounts for 43% of all primary energy consumption, as can be seen in Figure 8. The vast majority of this consumption is devoted to transport in all its forms: land, sea and air.

Hydrogen aspires to be a candidate, directly or indirectly, to replace many of the petroleum consumed in mobility, especially those with high tonnage and long distances. An exceptional case would be that of passenger cars, which can be decarbonised with lithium batteries, a much more efficient option, and which, if there are no mineral supply problems, could be the clear winner in the decarbonisation of these vehicles. However, as vehicles grow in size and range, direct electrification becomes increasingly complex. The limiting case is aircraft or large cargo ships, which are impossible to electrify directly with batteries. The borderline between hydrogen and direct electrification is long-haul trucks, which due to their size are on the borderline between what could be powered by electric batteries or may have to use hydrogen.

In any case, in terms of an economic comparison of the competitiveness of oil with green hydrogen, we will use two of its main by-products.

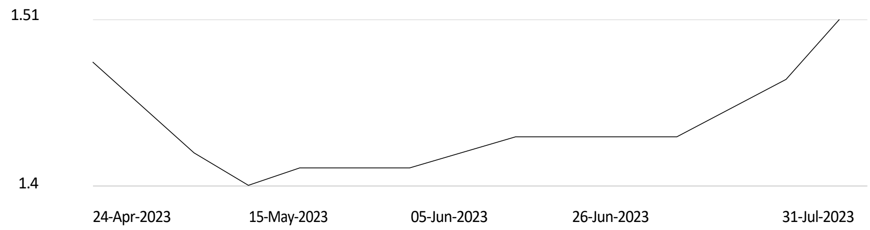
A. On the one hand, diesel, as an energy-carrying liquid for all heavy machinery on land, part of the maritime machinery and in versions similar to diesel (jet fuel) for aircraft. And we will compare it with the direct substitution of this fuel by hydrogen to see how competitive it is in approximate terms.

B. On the other hand, we are going to compare bunker fuel, the fuel par excellence of large cargo ships. But in this case, we will compare it with the price of green methanol, which could be its substitute. Remember that green methanol is a synthesis of green hydrogen and captured CO_2 , so it is indirectly indexed to the price of green hydrogen.

(A) As can be seen in Figure 15, the price of diesel in 2023 is around 1.4/1.5 € per litre, the retail price at petrol stations in Spain.

Figure 15 ⟶ DIESEL PRICES IN SPAIN IN 2023

Source: Global Petrol Prices [21].



If we start from that price and assume that a fleet operator could self-generate his own hydrogen, we see that the equivalent hydrogen price for the same energy would be 5.66 €/kg H_2 (Figure 16). Which makes it appear that green hydrogen at current diesel prices could be profitable since in section 2 it was calculated that green hydrogen could probably be produced in the range of €3 to €5.5.

Figure 16 → CALCULATIONS OF DIESEL PARITY WITH GREEN HYDROGEN

Source: Own elaboration

HYDROGEN DIESEL PARITY					
			News		
Diesel price	0,80	1,00	1,50	2,00	€/litre
Diesel density	850,00	850,00	850,00	850,00	kg/m3
Diesel price	0,94	1,18	1,76	2,35	€/kg
PCI diesel	11,94	11,94	11,94	11,94	kWh/kg
Gasoil price	79	99	148	197	€/MWH
Emissions cost	22	22	22	22	€/MWH
Competitive price H_2 green	3,36	4,02	5,66	7,30	€/kg
Cost of production H_2 (Paragraph 4)	3 a 5,5	3 a 5,5	3 a 5,5	3 a 5,5	€/kg

Although this apparently very positive result for green hydrogen, there are several nuances to be made. The first is that a hydrogen supply facility for vehicles has much higher compression, storage and dispensing costs than a simple hydrogen generation facility, and this has a negative impact on its competitiveness. In addition, the size of the production facility in a hydrogen plant is usually smaller, which also makes hydrogen dispensing to vehicles more expensive.

Secondly, it should also be noted that, although the assumption on which we are based is realistic, it is comparing the sale price at petrol stations with taxes compared to a self-generated hydrogen that would not pay taxes. If we were to compare the two fuels in purely energy terms, we would have to reflect in the comparison the price of diesel without taxes, which would probably be 0.8 €/litre, and then the profitability of hydrogen as an alternative fuel would be more compromised.

In any case, the reality for a logistics operator today is that he can self-produce his own hydrogen at prices in close competition with the price he has to pay including taxes at a filling station. However, if this phenomenon were to become popular, there would probably be some taxation of self-produced hydrogen for mobility. However, it is also an opportunity to fiscally encourage hydrogen mobility for captive fleets of high tonnage without the need for special state action.

In any case, hydrogen could become competitive also without taxation under certain assumptions. Since 0.8 €/litre would be the approximate price of diesel fuel today without taxes, and this would imply a necessary price of green hydrogen at 3.36 €/kg, a price that could be reached in the most optimistic assumptions calculated in section 2. However, it must be taken into account that these assumptions are very large installations, hardly applicable to hydrogen supply stations for vehicles, and also do not include the additional costs of compression, storage and dispensing of a hydrogen plant (hydrogen generation and dispensing station for vehicles).

(B) Considering the second scenario, the replacement of ship fuel oil by green methanol, we must first look at the fuel oil market. In this case, we have taken the Rotterdam market as a reference, where it can be seen that in recent years there has been a strong variation in price. As can be seen in Figure 17, from 2020 to 2023 the price of fuel oil has gone through a peak of 1000 USD/tonne, coming from prices of 300 USD/tonne in 2020 and, currently in 2023, it has moderated somewhat, remaining at around 600 USD/tonne. This is the reference price range that we are going to use to see the competitiveness with green methanol.

Figure 17 ⟶ PRICE OF FUEL OIL ON THE ROTTERDAM MARKET

Source: Ship & Bunker [22].

Based on this range of fuel oil prices (300-1000USD/tonne), the equivalence has been calculated, and on this basis, what the price of hydrogen should be that would allow the synthesis of methanol competitive with fuel oil.

Figure 18 ⟶ FUEL OIL PRICE EQUIVALENCE CALCULATIONS WITH GREEN METHANOL

Source: Own elaboration

FUEL OIL VS METHANOL PARITY (H)₂					
		News			
Fuel Oil Price	300	600	800	1000	USD/ton
PCI Fuel oil	11,22	11,22	11,22	11,22	MWh/ton
USD/Euro	1,09	1,09	1,09	1,09	
Fuel Oil Price	29	58	78	97	€/MWh
Methanol synthesis efficiency	75%	75%	75%	75%	
Price Hydrogen eq	22	44	58	73	€/MW
Emissions cost (approx)	22	22	22	22	€/MW
Competitive price H_2 green	1,46	2,19	2,68	3,16	€/kg
Cost of production H_2 (Paragraph 4)	3 a 5,5	3 a 5,5	3 a 5,5	3 a 5,5	€/kg

The calculations in Figure 18 show that the range of green hydrogen prices required for green methanol generated from green hydrogen to be competitive with fuel oil is 1.46 to 3.16 €/kg of H_2 . The price of hydrogen required at the current market price is 2.19 €/kg. It can therefore be concluded that green methanol generated from electrolytic green hydrogen is far from being competitive. Furthermore, it should be borne in mind that these are optimistic prices, as it has been assumed that obtaining CO_2 needed to synthesise methanol has no cost. Capturing CO_2 may have average costs of €40 per tonne which would make methanol more expensive. With the data and possible prices for green hydrogen today as calculated in section 2 (3-5.5 €/kg) fuel oil would have to return to its historical high of the last 2 years €1000/ kg for projects to be close to profitability today.

And despite the current lack of profitability, long-term projects have been announced, such as that of Maersk in Spain, which intends to invest 10 billion euros to produce methanol for its ships [23], at a time when the company is showing poor financial results [24]. This fact gives food for thought that even though green methanol can be 2-3 times more expensive than traditional fuel [25], it is still one of the few options for the maritime sector to move away from fossil fuels. The question is how fuel oil and green hydrogen prices will evolve in the long term. For parity to be reached, scenarios would have to occur in which fuel oil prices rise by at least 70% compared to today and green hydrogen prices moderate in the medium term to make projects of 2.5 - 3 €/kg profitable on a normal basis.

The other option is that we globally decide as humanity to leave fossil fuels behind in ocean shipping and take on the rising cost of freight due to fuel price increases with the added value of sustainability. This is complex as it would require many countries to agree.

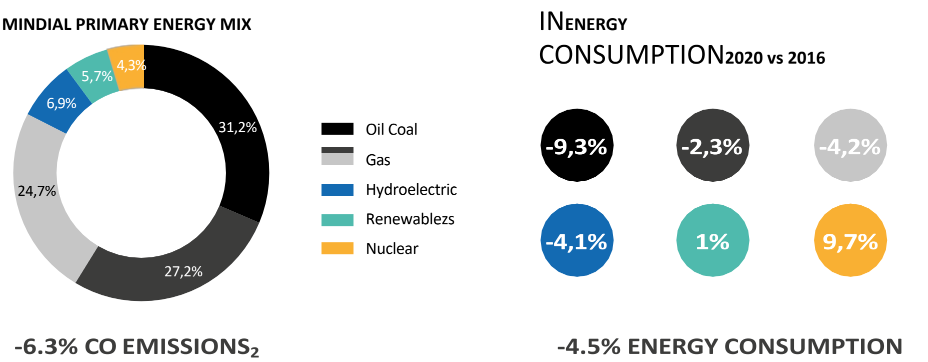
Chapter 7

Competition with metallurgical coal

The last fuel to be analysed in this report is coal. Although coal in Spain represents only 2.9% of consumption (Figure 8), this is not the case in other countries. In the global mix, it represents 27.2% of all primary energy (Figure 19). The main use in the world is electricity generation, but this use cannot be replaced by hydrogen as it comes from the electricity itself, at most it can be used to store it (albeit very inefficiently) as discussed in section 3.

Figure 19 → PRIMARY ENERGY SOURCES IN THE WORLD BY FUELS

Source: InterEmpresas [26].



However, coal is a material widely used even in Spain for the reduction of iron ore in blast furnaces. And in this process hydrogen is practically the only candidate for decarbonisation.

Iron is extracted in the form of iron oxide in the mines, and to convert it into iron, or steel, the oxygen atoms it contains must be removed. For this function, a reducing agent (a fuel) is required, and this is where metallurgical coal comes in. In the usual blast furnace processes, coal combines with the oxygen in the oxide to generate CO_2 and iron or steel ($_{Fe2O3}$ + $_{C \rightarrow 3/2CO2}$ + 2Fe).

This is not a process in which coal is only a fuel and can be substituted by any other energy source. It is a process in which coal serves as a chemical reducing agent and that is why other reducing agents are needed to replace it.

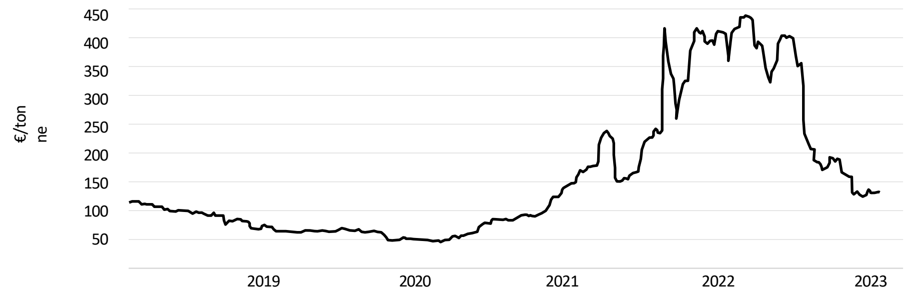
Recently, direct reduction iron ore (DRI) plants are being promoted due to the lower emissions they entail. These plants use natural gas as the reducing agent for iron ore. In addition, these plants can be converted to hydrogen, using hydrogen as the reducing agent. The difference is that hydrogen as a reducing agent "steals" the oxygen from the iron ore and generates only water, not CO_2

($_{Fe2O3\ \ +2H2 \rightarrow 3H2O}$ + 2Fe). This is why hydrogen is one of the main ways to decarbonise the iron ore reduction metallurgy sector.

We are going to try to study the parity of the price of coal as a fuel and reducing agent with green hydrogen. To do so, we will start from the price of coal, which has fluctuated in recent years between €50 and €450/kg, currently standing at €134/tonne (Figure 20).

Figure 20 → COAL PRICES

Source: Trading Economics [27].



Taking into account that to perform the same reducing function as 3 kg of coal, 1 kg of hydrogen is needed (stoichiometry of the reaction), and that for each kilogram of H_2 used to replace coal as a reducing agent, 11 kg of CO emissions are saved$_2$ (stoichiometry of the reaction). Calculations have been made in Figure 21 for the price of H_2 that would be necessary to be competitive with coal as a reducing agent for iron ore.

Figure 21 → COAL PRICES CALCULATIONS OF HYDROGEN AS A SUBSTITUTE FOR COAL REDUCING AGENT

Source: Own elaboration

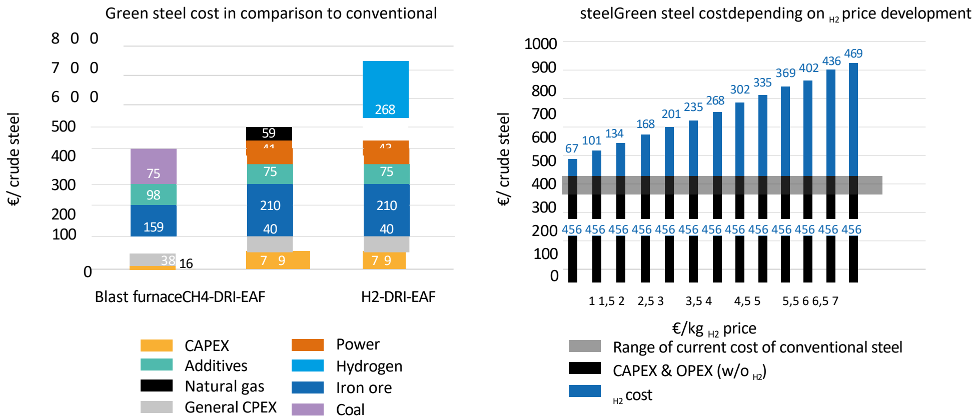
CARBON HYDROGEN PARITY (AS REDUCTANT)				
	News			
Ratio of oxidants Carbon vs H_2	3	3	3	
Carbon Price	134	300	450	€/tonne
Price H_2 (without emissions)	0,402	0,9	1,35	€/kg
CO savings$_2$ per kg H_2	11	11	11	
price CO_2	80	80	80	
Competitive price H_2 green	1,282	1,78	2,23	€/kg
Production cost H2 (Paragraph 4)	3 a 5,5	3 a 5,5	3 a 5,5	€/kg

The result is that even at €450/tonne of coal (peak price) and taking into account the cost of emissions (€80/tonne CO_2) it would be necessary to produce hydrogen at a price of €2.23/kg to make it competitive. This cost of H_2 production is outside the range of possible prices at which green hydrogen can be produced today. In fact, today the price of coal is more like €134/kg and at that price hydrogen costs of €1.2/kg would be necessary, which makes the operation even less profitable. However, it should be noted that metallurgical coal is often priced higher than the "ordinary" coal with which the comparison has been made, which would give hydrogen an advantage as a reducing agent in some markets.

In any case, for green hydrogen to become profitable with coal as a reducing agent, it would be necessary at least for the price of coal to return to its highs of €450/kg and for the costs of CO emissions$_2$ to double to €160/tonne. Under this assumption, and assuming that green hydrogen can be generated below €3/kg, green hydrogen would be competitive with coal as a reducing agent. As an external reference, it can be seen in Figure 22, Comparison of costs per tonne of steel by different methods [28], how the estimated price of green steel generated by hydrogen DRI is almost double that of coal-fired blast furnaces. In turn, it can be seen how the price of hydrogen would have to be at least below €2 per kilogram to approach the current price of natural gas DRI. From Figure 22, it can be concluded, as from this report, that green hydrogen is too expensive at present to replace conventional reducers (coal and natural gas) and therefore, if it is implemented, high cost overruns will have to be assumed, with the counterpart of CO savings$_2$.

Figure 22 → COMPARATIVE COST PER TONNE OF STEEL BY DIFFERENT METHODS

Source: LBST [28]



In addition, as coal is used worldwide as a fuel for other types of processes (boilers, cement plants, etc.), it was also considered relevant to analyse its competitiveness as a general energy fuel (not as a reducing agent). Figure 23 shows the calculations of competitiveness with hydrogen for the price range (134-450 €/tonne).

Figure 23 → CALCULATIONS OF HYDROGEN AS A SUBSTITUTE FOR FUEL COAL

Source: Own elaboration

CARBON-HYDROGEN	PARITY (AS FUEL)			
	News			
PCI	7	7	7	MWh/ton
Carbon Price	134	300	450	€/tonne
Carbon Price	19	43	64	€/MWh
Emissions cost	32	32	32	€/MWh
Competitive price H_2 green	1,7	2,5	3,2	€/kg
Cost of production H_2 (Paragraph 4)	3 a 5,5	3 a 5,5	3 a 5,5	€/kg

And while the range of hydrogen prices needed to make it profitable is far from current production prices (section 2), it is closer to profitability than in the case of coal as a reducing agent. In this case, at the peak coal price of 450 €/tonne, hydrogen at 3.2 €/kg would have been sufficient to make it competitive, and that is a price in the range of possible green hydrogen prices today. Even so, at the current coal price (134 €/tonne) it would be necessary to produce green hydrogen at 1.7 €/kg, which is unfeasible in today's market.

Chapter 8

Financing, public and private

As has been observed throughout the report, practically none of the uses of green hydrogen are profitable today, based on current competitive fossil fuel prices. Yet hydrogen is seen as necessary as a society to decarbonise at least some of the industrial processes. This is why agencies in many countries have proposed public funding programmes for hydrogen projects, in order to promote early implementation. The hope is that once projects begin to be developed and electrolysers produced, prices will fall due to economies of scale (mass production) and hydrogen can then become profitable.

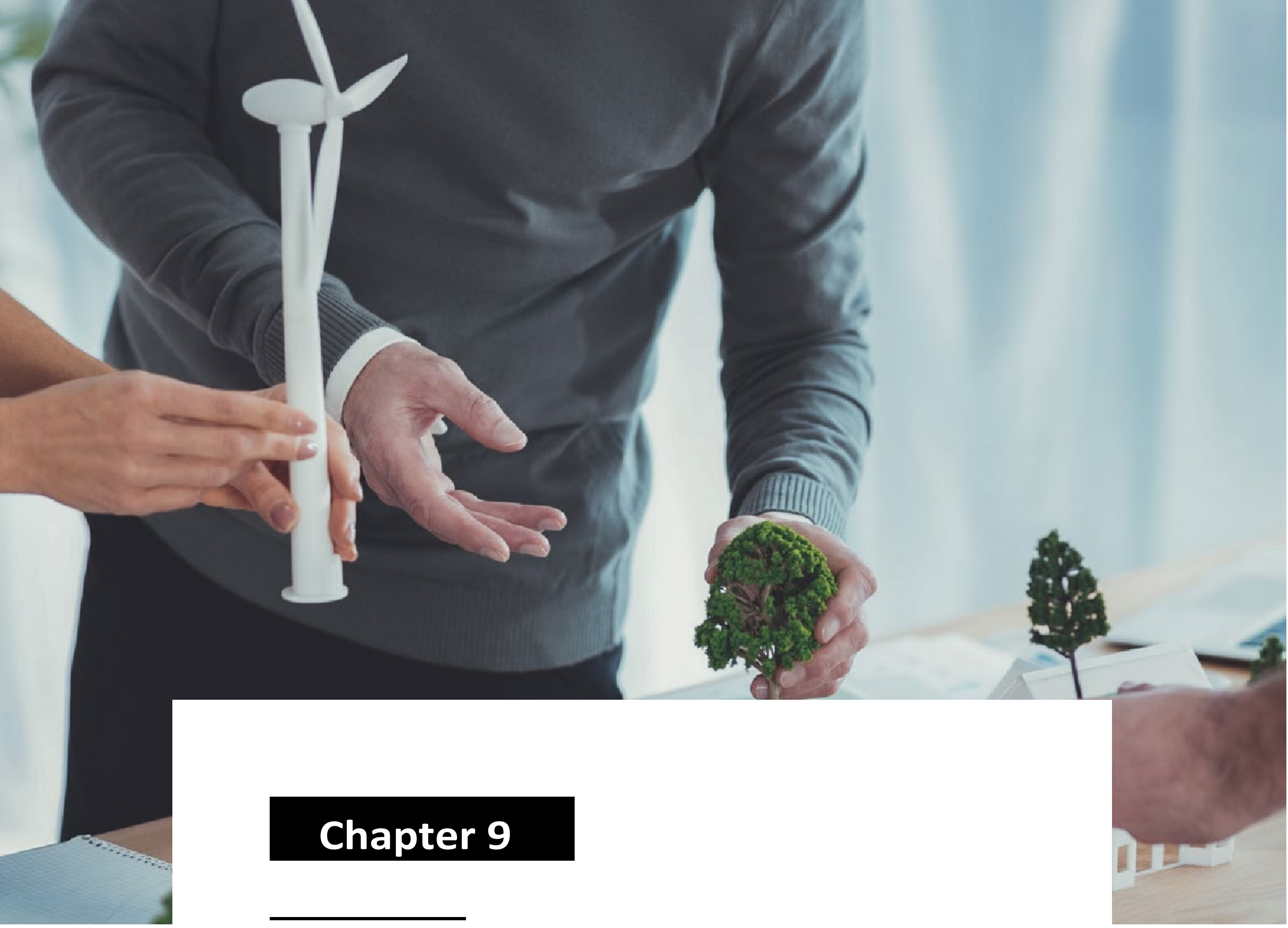
The problem, at least in European funding programmes such as NEXT GENERATION, is that they are proposing funding for the CAPEX of the equipment (the investment) and this represents less than 50% of the total costs of the project throughout the life of the electrolyser. And yet most of the costs depend on the available energy, which is not being financed. In addition, the very high volume of investment in announced projects makes it impossible for the drive to be public, as it would imply a very high level of market intervention by the state, so that a large part of the announced projects will not be eligible for public funding.

A more effective approach would be to finance the final price of hydrogen as was done with photovoltaic installations in the past, by financing the price of energy. Finance the euro per kilogram in the first years until it becomes profitable on its own or because other fuels become more expensive. In this way, no money would be lost on projects left half-finished, as only the hydrogen produced and sold would be paid for, and the entire project would be financed, not just the CAPEX.

On the other hand, even in projects that already have public funding, they are having problems to bank-finance the rest of the project. This is because banks do not have the capacity to assess the risks of the technology and the market. There is no relevant prior experience to secure investments and in many projects the final consumption of hydrogen (and associated cash flows) is not guaranteed.

As highlighted in section 1 of the report, the problem is the pace at which technology is being pushed to grow, which does not allow for an organic learning curve. On the contrary, technology is being forced to advance at rates for which neither the technology nor public or private funding is ready.

A technology that is not yet profitable can grow on the basis of public subsidies, but the rate at which it can grow in its early stages is slow, as public money is limited and without market testing you can make serious errors of perspective. Experience says that you have to grow on the basis of relevant solid experiences in the previous volume step, and on the basis of that, create the next stage. Green hydrogen was a non-existent entity in the energy landscape 4 years ago and it is complex to promote it publicly at the pace that is needed in the sector, because it implies jumping several steps at once and that has high risks.



Chapter 9

Conlcussions

- This report has attempted to analyse the competitiveness of hydrogen, as well as the barriers why, although there are currently many project announcements, most of them do not turn into real projects.

On the one hand, it has been analysed how the need for a general decarbonisation of the economy is driving the hydrogen sector faster than its organic growth and this is leading to attempts to use hydrogen for uses where it is probably not the best option or where it is currently far from being competitive.

At the same time, the existing pressure from the photovoltaic investment sector to continue promoting installations, despite the growing problems they are encountering with access to the grid, which is beginning to be saturated during daylight hours, has been exposed. This pressure is being transferred to the hydrogen sector, as a conduit for this energy. But the reality is that the sector is not yet ready for the volume of investment and profitability at which photovoltaics operate and, furthermore, photovoltaic developers are not familiar with the dynamics of the sector and often make mistakes in their business approaches, which leads to stagnation in announced projects.

Subsequently, some assumptions were made to make an approximate calculation of the cost of green hydrogen in projects in Spain, from which a range of possible prices was obtained for different green hydrogen projects of between €3 and €5.5 per kilogram of hydrogen produced. The difficulties in which the projects are being viewed by the manufacturers have also been highlighted, in terms of the lack of guarantees of the electrolysers or of notable experience in the operation of the equipment on the part of the manufacturers, which generates uncertainty in the durability and long-term performance of the equipment, risks that are slowing down some projects.

On the other hand, the emissions saved by using hydrogen instead of fossil fuels are not only an environmental but also an economic advantage, as many applications are forced to pay for these emissions. In this report, these advantages have been quantified economically, with respect to the main fossil fuels, obtaining data on how many euros per kilogram of hydrogen used are saved in emissions by substituting hydrogen for each fuel (1.1 €/kg coal, 0.7 €/kg diesel, 0.6 €/kg natural gas).

With regard to fossil fuels, it has been shown that the total or partial substitution of natural gas by hydrogen for combustion has its greatest exponent in the phenomenon known as "blending". This phenomenon would allow a new grid where renewables could discharge their energy in the form of hydrogen, blending it with natural gas. However, it has been analysed that the competition of hydrogen with natural gas for combustion at current gas prices is very bad as green hydrogen is much more expensive than natural gas for that function. The price of gas is simply too low for green hydrogen to compete in direct combustion. We would have to see natural gas prices above 100 €/MWh again in the short term for hydrogen to be competitive.

However, in the case of grey hydrogen (hydrogen generated from natural gas) which is used as an input to the chemical (non-energy) industry, the numbers are more favourable to green hydrogen, and it is also the only current decarbonisation option. The result in this case is that green hydrogen would have to cost €2.9/kg to be competitive with grey hydrogen today. The profitability of green and grey hydrogen is close, and only with slight increases in the estimated price of natural gas in 2024 and CO $costs_2$, together with investment subsidies for electrolysers, these types of projects could begin to be installed in the short term. Moreover, it is worth noting that in these cases green hydrogen is the only decarbonisation option, so the push for public subsidies in this case is being stronger. Green hydrogen as a chemical input replacing grey hydrogen is the strongest and most profitable bet in the whole green hydrogen universe. They will certainly be the first large-scale projects to come on stream.

Analysing diesel prices, it has been concluded that a logistics operator could self-generate its own hydrogen at prices close to profitability. However, this phenomenon happens mainly because diesel pays a lot of taxes and H_2 does not. However, it could be a fact that is encouraged by administrations as an incentive for the use of hydrogen in mobility. Taking taxes out of the equation, the profitability of hydrogen as a mobility fuel is compromised, assuming the most likely price scenario of 3.7 €/kg H_2 .

Green methanol has been analysed in the market for large ships as a possible substitute for fuel oil. Green methanol is synthesised from green hydrogen and CO_2 . It has been concluded that fuel oil would have to return to its 3-year high prices (€1000/tonne) for green methanol to be competitive, and even then green hydrogen would have to be generated at €3.16/kg, which is a very optimistic price.

Despite the current lack of profitability, long-term projects have been announced, such as that of Maersk in Spain, which intends to invest 10 billion euros to produce methanol for its ships [23], in a difficult economic situation for the company [24]. This fact makes us reflect on the fact that, despite the fact that green methanol can be 2 to 3 times more expensive than traditional fuel [25], it is still one of the few options for the maritime sector to leave fossil fuels behind.

Looking at coal as the last of the three major fossil fuels, its main hydrogen substitutable use is iron ore reduction. For this use, it has been calculated that even at the highest coal prices of the last two years (€450/tonne), green hydrogen at €2.23/kg would be needed to be competitive, around 35% cheaper than the most optimistic hydrogen price scenario today. And at today's prices (134 €/kg) the hydrogen price needed would be 1.28 €/kg. In the light of these data, it can be concluded that green hydrogen is unlikely to be competitive for iron ore reduction in the medium term, so that if this process is to be decarbonised, higher energy costs and higher iron ore prices will probably have to be assumed.

Finally, this report has analysed how public funding is trying to compensate for the low or non-existent profitability of hydrogen as a substitute for fossil fuels. But given the high level of private investment announced, it is impossible for all projects to receive public co-funding, as this would be a huge public intervention in the market. Moreover, at least in Europe, CAPEX (investment) rather than OPEX (operating expenditure) is being financed, when the latter is the most important part of the plant's full lifetime costs, which means that the public contribution is often not large enough to make private investment profitable.

Expectations for hydrogen as an energy carrier are extremely high and are unlikely to be met. The main reason is that it is being pushed towards accelerated growth by taking risks that would not be contemplated in the case of organic growth. Considering that most of its applications are far from profitable, the ensuing projects depend on the availability of public funding or subsidies. And as these are limited, there are many projects in the analysis period, noting that there is no profitability in them and waiting for subsidies or changes in the fossil fuel market to make them profitable. This is the main reason for the slow evolution of the announced projects.

It is worth remembering that hydrogen is in its infancy as a technology in industrialisation, and despite the very high expectations, a new technology is not usually profitable in its infancy, so it is not a candidate for direct private investment on its own. Much of the expectation is based on investors who, not knowing the technology, believe that it is profitable, when it is not. And they themselves are disappointed when they crunch the numbers on their own projects, finding that there is usually no return without subsidy in most cases. Therefore, the volume and direction of the sector will be defined by a public body on the basis of subsidies which, most probably, will not be the announced volume of projects, due to the limitation of public money. Furthermore, there is a risk of public funding for projects that will never become profitable because the public body does not have the market testing that dictates how close to viability the projects are in a scenario of organic development of the sector.

In conclusion, and as has been made clear throughout the report, hydrogen is an interesting option for decarbonising many processes. But its cost is and will most likely be higher in the medium term than that of its fossil alternatives. Therefore, there are only two ways forward: either wait for fossil fuels to rise in price and make green hydrogen profitable, or assume as a society that being sustainable will mean a higher cost than expected and finance this additional cost in the form of public intervention or an increase in the price of consumer products and services.

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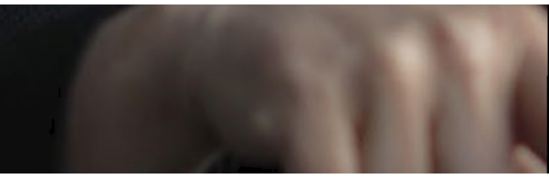

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