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DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

TECHNOLOGICAL ASSESSMENT OF HYDROGEN

(FUTURE SCENARIOS: SOCIOLOGICAL, ENVIRONMENTAL, ECONOMIC, AND ENERGETIC ASPECTS)

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1 Abstract.

Nowadays, the term energy transition is coming into vogue, as many countries are adopting the climate change agenda across the world to achieve sustainable development goals and change from non-renewable energies to those coming from inexhaustible energy sources, that are more efficient and less polluting. Power-to-hydrogen is an auspicious solution for storing variable renewable energies.

The role of hydrogen up till now in the industry is crucial not only to create products in different sectors but for the storage of energy and the creation of new energy produced with hydrogen which is the goal for the future of the industry sector.

Clean hydrogen is basking in the glory of the tremendous momentum with the unprecedented political discussions and the number of policies and projects occurring worldwide. Further studies are primordial to ensure a significant share of hydrogen in the energy system.

This paper's main goal and objective were to analyse the implementation of hydrogen within this transition and to come up with a few scenarios in the near future for this new technology in the environmental, social, energy, and economic fields. The scope of this assessment was to assess future design for green, blue, grey, and turquoise hydrogen technology regarding the areas mentioned above, along with the risks and opportunities that could arise during this time.

By comparing the current situation and the predicted future scenarios of hydrogen generation technologies, the goal is to respond to these questions: ¿What are the main differences among the different hydrogen production technologies? ¿What are the possible consequences of implementing this technology, and how could it be implemented with less detrimental effects?

From the derived scenarios, the literature review showed that in the event of an economic decline, the reduction of financial resources will deter the continuous improvement of technology, and governments will create supportive schemes and reduce taxes to help citizens cope with the crisis and unemployment rates. By contrast, in the scenario where an improvement in technologies occurs, an increase in employment will be discernible, striking techniques will decrease energy consumption and there will be an imminent reduction in carbon dioxide emissions. In anticipation of external events, relocations and alterations in different sectors would take place, leading to social penurious conditions. The Multi-Criteria Decision Analysis revealed that green hydrogen production is the best procedure for a more sustainable system and the least propitious technology was the grey hydrogen generation.

2 Introduction.

Due to the current necessity of implementing greener energies and coupling them to the electricity grid, the last decade has been a precursor to achieving this, nevertheless, there is still a long path to go in every area of sustainability. Modern technologies, better policies, increasing interaction with society, creating international agreements, local awareness, and so forth.

This paper is important to interpret the role of hydrogen more dynamically and holistically in contemporary times and how production methodologies have particular benefits and impediments over others. The main goal is to provide insight into hydrogen technologies and a broader approach to possible circumstances in the event of specific scenarios in the following years.

Some studies have been made about future scenarios in the past years and both methodologies used in this paper, Multi Criteria Decision Analysis (MCDA) and Sustainability Assessment Framework for Scenarios (SFDA) have been used by diverse authors to compare and demonstrate hydrogen production but with distinguishable variations.

An example of the evaluation of future scenarios including environmental perspectives and social issues is shown in the paper by Lucas et al, where their objective was focused on enhancing the capacity for evaluating the general sustainability of transportation choices and accessibility to the amenities as an indicator of social viability (Lucas, Marsden, Brooks, & Kimble, 2007). Another example is the paper of Bent Sørensen who constructed different energy demand scenarios for Germany, Sweden, Norway, Finland, and Denmark and he demonstrated that the deployment of temporal hydrologic reservoirs in the Nordic regions serves as a demonstration of how efficiently an energy system may be established (Sørensen, 2008).

For instance, an example of MDCM, in the paper by Bartosz Ceran, he compares multiple hydrogen scenarios with diverse criteria such as environmental, technical and economic factors to produce highly pure hydrogen using photovoltaic panels in Poland (Ceran, 2020). Using various MCDM techniques, some studies have been applied in the discipline of hydrogen production technologies, for example, applications of these analyses using fuzzy Analytical Hierarchy Processes, as is the case of the paper by (Acar, Beskese, & Temur, 2018) where they evaluated five generation techniques relying on their energy source. They came to the conclusion that water electrolysis will become a crucial technology for sustainable hydrogen production in the future as production costs drop.

An additional MCDA using a combination of two decision-making tools to create a mathematical framework for evaluating the sustainability of various hydrogen generation processes in unpredictable circumstances. It was determined that among the four options analysed, including coal gasification, steam reforming of methane, biomass gasification, and wind turbine electrolysis, the process of biomass gasification was found to have the highest sustainability (Ren & Toniolo, 2018).

In order to achieve sustainability is necessary an integrated approach that takes into consideration environmental concerns along with economic development and social issues while meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). That’s why it is primordial to focus on every element of sustainable development to progress successfully to the new era of renewable energies.

Depending on production methods, energy used, and related emissions, hydrogen is classified in a range of colours; grey, blue, green, pink, yellow, and turquoise, or even some other classifications. Among all processes to obtain hydrogen, the most suitable to achieve a sustainable energy transition and decarbonisation is green hydrogen which is produced from renewable energy sources. At the same time, this green hydrogen can help augment the system's flexibility and storage options to make the transition of these renewable energies into the market smoother.

The main challenges involved in hydrogen uptake are safety, efficiency, effective distribution, and affordable storage (Moradi & Groth, 2019). Even though there are some risks to making allowances, hydrogen can be handled and used safely with adequate technique handling and engineering methods.

A technology assessment is a systematic process of analysing future consequences of emerging technologies and according to Grunwald, the primordial and common expectations of technological assessment processes should include: some orientations of future effects of such technology, inform and enable policymaking, detect and resolve conflicts that could arise from the development and implementation of new technologies and enable the social shaping of technology. Different actors should interact, such as parliamentarians, experts, and society. It has to be democratic and unbiased; everybody should know about the new technology and its pros and cons (Grunwald, 2019).

Integrating these environmental and social assessments is a primordial characteristic of SAFS, that allows the visualisation of the possible consequences of potential environmental degradation on social conditions and human wellbeing (Arushanyan, Ekener, & Moberg, 2017). Technological Assessment (TA) was created to foresee the inadvertent negative repercussions of technical innovations to simplify and enhance policymaking (Palm & Hansson, 2006).

Assessing future scenarios can be complex to interprete and therefore to provide quantitative data (Höjer, et al., 2008). There are different examples of scenario development and an assessment of sustainability consequences like those scenarios trying to predict the possible implications of new enacting policies, those focusing on the consequences of implementing new technologies in the market, or others analysing the interactions of human beings within society (Arushanyan, Ekener, & Moberg, 2017).

2.1 Hydrogen Characteristics

Hydrogen is the most bountiful element in the Universe, which is found on our planet Earth mainly in water and organic compounds, but even though it is found in many combinations with other elements, as a gas hardly ever occurs. Among the main benefits that this element encompasses is the tremendous amount of energy per unit mass which makes it the lightest fuel and the richest, and the heat energy produced during its combustion is higher than other carbonaceous fuels such as petroleum, graphite or paraffin, or also wood or castor oil (Zhang, et al., 2015). The energy liberated during its combustion is higher in comparison with methane, gasoline, and coal by a factor of 2.4, 2.8, and 4 times more, respectively (Wang, 2012).

Hydrogen is certainly not an essential energy source, instead an energy carrier and must be stored to overcome daily and seasonal fluctuations between supply and demand (Al-Baghdadi, 2020). Hydrogen can originate from a great variety of energy sources such as natural gas, coal, biomass, residues, sun, wind, and nuclear power or a mixture of them (Ogden, 2002). Hydrogen can react chemically with high conversion efficiency, yielding essentially zero emissions while using it.

2.2 Hydrogen Production

Natural gas is currently the prime source of hydrogen generation, standing for three-quarters of the global hydrogen production of around 70 million tonnes annually and generating about 843 metric tonnes of carbon dioxide emanations per year. Nowadays only 0.1% of the global hydrogen production comes from water electrolysis (IEA, 2019).

Among the main methods used to produce hydrogen are steam methane reforming somewhere in the region of 48%, oil reforming at around 30%, coal gasification with 18% of the total production, while ammonia and methanol playing a minor role (Wang, 2012). One of the main processes worldwide for hydrogen production is water electrolysis. At present, the three most significant technologies for electrolytic hydrogen production are alkaline, polymer membrane, and ceramic oxide electrolytes (Momirlan & Veziroglu, 2002).

The main hydrogen production pathways encompass four main categories, which are thermochemical, electrolytic, direct water solar splitting, and biological processes (Efficiency & Energy, Fuel Cells, 2022). Notwithstanding, there are other subcategories like photocatalytic processes and a few others that are considered emerging technologies that hold less mature alternative methods (Momirlan & Veziroglu, 2002).

- ✓ Thermochemical: Fossil fuel feedstock is utilised to create hydrogen in this process. The use of carbon capture and storage (CCS) is foundational to making it more sustainable. The most common and cheapest way to generate hydrogen is currently steam methane reforming (SMR) which depends on natural gas and coal gasification predominantly from methane gas mixed with other hydrocarbons (Osman, et al., 2021). Four steps are necessary to carry out the reforming such as desulfurisation, steam reforming, water and gas shift, and purification (Wang2012). Other thermochemical routes are partial oxidation, thermal reforming, coal gasification, pyrolysis, and supercritical water gasification (Nanda, Li, Abatzoglou, Dalai, & Kozinski, 2017)

  The main mechanisms and industrial applications to produce hydrogen from pyrolysis are plasma, thermal cracking (fluidised bed), moving carbon bed, molten metal and salt, liquid metal (bubble column and condensing reactor), and thermocatalytic (Sánchez-Bastardo, Schlögl, & Ruland, 2021). The quality and amount of item yield from pyrolysis chiefly rely upon specific attributes, for example, temperature, disintegration time, warming rate, biomass organisation, working strain, and reactor structure. Temperature and disintegration time are the two most significant elements for effective pyrolysis and the final product (Kannah, et al., 2021).

- ✓ Electrochemical: Utilisation of electrolysers that consists of a cathode and anode separated by an electrolyte and with the induction of electricity, splitting water into ions of hydrogen and water (Efficiency & Energy, Fuel Cells, 2022). This technology is globally used, but it's expected to become more critical and continue to play a more significant role in no time.

  Electrolysis provides a more suitable option to help to flat the peak of energy demand during the energy transition. The electrolyser is made up of the stack, which is where the actual separation of water into hydrogen and oxygen occurs, and the system level of the plant, which includes electricity supply, the supplement of water, purification, compression, hydrogen buffers, and hydrogen treatment. The two elements of the electrolyser, either the stack or the system level are paramount because they have similar costs (IRENA, 2020).

- ✓ Direct Water Solar Splitting: Also called the photolytic or photovoltaic process, involves the direct use of solar light to produce chemical energy into hydrogen. . The main approach to producing hydrogen from Direct Water Solar Splitting is by Photo Electrochemical cells (PEC). The main methods for PEC splitting production are; combined PV-electrolysis systems, photoelectrode-based systems, and photocatalysts-based slurry systems (Lopes, Dias, Andrade, & Mendes, 2014). PEC is a promising new technology where the only difference from photovoltaic solar energy is the immersion of semiconductor materials in an alkalinised liquid, and the sun rays produce the water-splitting process.

- ✓ Biological: Biological processes are environmentally friendly. Microbial biomass conversion benefits from the ability of microorganisms to absorb and digest biomass and release hydrogen. Different microorganisms such as algae, cyanobacteria, photosynthetic bacteria, photoheterotrophic bacteria, and chemoheterotrophic bacteria, together with sunlight and organic matter, are involved in the biological hydrogen production processes capable of producing hydrogen (Ding, Yang, & He, 2016). The three major mechanisms for this production are; fermentation (dark fermentation and photofermentation), biophotolysis (direct and indirect), and bioelectrochemical systems such as microbial electrolysis cells (Gopalakrishnan, Khanna, & Das, 2019).

The eminent challenge with the biophotolysis of water and photofermentation to take into consideration is the low production of hydrogen due to the reason that oxygen is yielded, and it inhibits the development of hydrogen reactions (Poudyal, et al., 2015). Among all microorganisms, hydrogen production by green algae is allegedly the most economical and useful in water usage (Das & Veziroglu, 2008). Dark fermentation is mainly an adequate practice to treat biomass residues due to its high hydrogen production rate (Ding, Yang, & He, 2016).

2.3 Colour classification

Hydrogen is generated from a variety of primary sources, including renewables, natural gas, coal, or nuclear power, and a plethora of production techniques, and according to that, hydrogen is classified by colours. This colour assignation helps to delineate these mechanisms mentioned above, along with the emissions and distinct effects on the environment.

***Grey Hydrogen*:** Hydrogen is produced by fossil fuels, predominantly from natural gas and coal, which leads to carbon dioxide emissions.

Blue Hydrogen: Hydrogen is produced by using carbon sources, but with the difference that here carbon capture and storage are implemented, which in turn helps to reduce GHG emissions to the atmosphere; blue hydrogen is also considered “low-carbon” hydrogen.

Green Hydrogen: Hydrogen is obtained via electrolysis using renewable energy to produce electricity. It is sustainable only if the process to extract it also is**.**

Pink/Red/Purple Hydrogen: Hydrogen is produced from nuclear power electrolysis.

Turquoise Hydrogen: Hydrogen is produced by methane pyrolysis, which splits methane into hydrogen gas and solid carbon.

***Yellow Hydrogen**:* Hydrogen is produced by electrolysis using grid electricity made from different sorts of energy either renewable or non-renewable. In the United States of America, the yellow colour classification solely comes from nuclear plants as the pink/purple/red colours (Group, 2022).

White Hydrogen: Hydrogen is taken mostly from its natural gaseous structure from different deposits on Earth. There is not yet a viable strategy to extract this hydrogen.

Nonetheless, for this research, the colours used for the principal methodology and overhaul were grey, blue, green, and turquoise.

2.4 Hydrogen Storage

Even though the hydrogen energy has a plethora of advantages, its storage is a fundamental key in developing reliable and better ways of compressing hydrogen. Currently, hydrogen storage methods encompass high-pressure storage by using hydrogen, metal hydrides and carbon materials (Zhang, et al., 2015).

Different processes and techniques are used to store hydrogen. They can be physical and chemical. Physical storage includes liquefied storage, compressed gaseous hydrogen storage, and cryogenic-compressed storage (Barthélémy, 2012). Chemical storage contains compounds such as ammonia, metal hydrides, and toluene that carry hydrogen. Once it has been converted into a suitable form, it can be stored and transported with different techniques through gas pipelines, trucks, trains, or ships (Moradi & Groth, 2019). Hydrogen can be stored with no risks as a gas in subsurface formations at temperatures between 25 and 130 °C and pressures between 5 and 30 megapascals (Osman, et al., 2021).

It can be stored as a liquid, in gaseous form by pressurised or compressed gas storage, or stored in metals at a subatomic level, via absorption or on the top of solids by adsorption (IRENA, 2022).

Hydrogen has the highest storage density when it is liquefied, but to do that, it must be brought to its critical pressure and then reduce its temperature to minus 253 Celsius degrees, which in turn, makes it a complex, time-consuming, and high-demanding energy process. The minimum amount of energy needed to liquefy hydrogen is 15.1 MJ/kg; that energy currently amounts to over 30% of the total energy stored (Sørensen & Spazzafumo, Hydrogen, 2018).

The transportation of hydrogen over long distances is more profitable as a liquid than gaseous hydrogen because a liquid truck can keep a higher amount of hydrogen than a gaseous truck. Technically speaking, a road truck transporting compressed hydrogen might usually carry around 300 or 400 kg of H_2 and have the capacity to refuel approximately 100 vehicles. A tanker carrying liquefied hydrogen carries a more extensive reservoir from roughly 2.5 to 3.5 tonnes, so it refuels about 1000 cars (Melaina & Penev, 2013). Nevertheless, one disadvantage of liquid hydrogen is the unavoidable loss from evaporation due to the heat flow from the exterior into the storage vessels. Therefore, creating high-standard insulation techniques is significant to avoid boil-off losses (Viswanathan, 2017).

Pairing storage and transportation generally involve several components such as hydrogen demand, infrastructure like pipelines, and distance (Hartley, et al., 2019).

2.5 Security and Risks

Management of hydrogen is of the utmost importance because it has a very low density and it is relatively flammable and explosive. Throughout history, many incidents have surged from its mishandling.

Generally, hydrogen represents no major new dangers related to other fuels; therefore, hydrogen energy is relatively safe. The complications arise when errands are completed along the hydrogen's value chain, from its creation to its usage: the filling of tanks, for instance, the transportation and maintenance. However particular difficulties vary between the diverse applications: the installation and operation of production plants is a common denominator among every one of them, and this infers all actions to ensure the well-being of the establishment and the employees.

Using a catalogue of hydrogen-related events recorded by the Department of Energy of the United States, from a period between 1999 and 2019, it was summarised that most of the incidents were produced in laboratories representing 38.3%, charging stations for hydrogen, and businesses that deal with hydrogen came in second and third, with 10.6% and 9.0% of the total, respectively. Additional investigation into the specifics of laboratory mishaps indicated that two primary contributing factors to the occurrences were human mistakes and equipment malfunction (Wen, et al., 2022).

A few of the hazards that hydrogen possesses are the high pressures that attain during different processes or storage techniques. When it reaches high pressures it can lacerate the bare skin and it could also asphyxiate in isolated places without ventilation. As a cryogenic liquid, it can burn eyes and skin or produce injuries in some body tissues by long exposure to very low temperatures. It also could affect the lungs from cold vapour. An explosion could be triggered when a vessel experiences a structural failure, where there may be several ignition sources, including heat from excessive metal stress, sparks produced by debris, damaged cables, et cetera (Idaho National Engineering and Environmental Laboratory, 1999).

Whenever a spillage or hydrogen leak happens, a stream is liberated and changes into a crest that swiftly rises due to buoyancy and it forms a mixture of air and hydrogen. Hydrogen ignites when the mixture's concentration comes into contact with little ignition energy. As the fire persistently speeds up, the explosion could rapidly materialise (Yang, et al., 2021).

2.6 Industry

Hydrogen is almost ubiquitous in sundry industry sectors such as refineries, as direct harness from fuel cells in transportation, chemical feedstock, methanol and ammonia production, metallic ore reduction, hydrochloric acid production, also in the food industry where it is used to produce hydrogenated vegetable oils like margarine and butter, as a searching gas of certain leaks, in the pharmaceutical industry for the production of hydrogen peroxide as a steriliser, gas chromatograph, reducing agent, etcetera (Brown AFIChemE, 2019).

Hydrogen is at present utilised in processing plants to lessen sulfur content in oil items to satisfy explicit environmental guidelines, and to redesign bad quality weighty oil. The updated yearly H2 production around the world for all sectors is near 120 Mt (Global CCS Institute, 2021). On a worldwide scale, about one-third of the world's demand is met by hydrogen acquired as a secondary product of other treatment facility processes, while the rest is generated regionally by SMR or provided by outer suppliers (Noussan, Raimondi, Scita, & Hafner, 2021). That means about 76% of the whole hydrogen production is originated from natural gas, either SMR or Coal Gasification (Cavana & Leone, 2021).

The Haber-Bosch process is a very popular and modern technique for the development of ammonia to date and includes the immediate mix of hydrogen and nitrogen under a pressure of around 150 bar and a

temperature of 400 Celsius degrees within the circulation of a catalyst. NH3 also helps to create ammonium nitrate, which is a fertiliser and is essential for some family cleaning items. Just behind petroleum or oil plants, ammonia production is the second biggest usage of hydrogen (Darmawan, et al., 2022).

Hydrogen in its liquid composition is usually employed in the space industry to boost propellers as a fuel, due to its high density and a minority of risks in terms of storage pressure in contrast with its gaseous form as compacted gas (Allevi & Collodi, 2017).

A contemporary report for the north of Europe predicts that regardless of the moderately low 45% cycle productivity, power-to-gas power capacity would be valuable and financially feasible in a high-renewables situation for 2050. The report presumes that hydrogen storage and electricity generation are more gainful than their utilisation in the industry (IRENA, 2019).

The International Energy Agency expresses that by 2050, steel delivered from green hydrogen will be only 10% or less. The steel industry depends on coal, which creates a gripping scenario where at the expense of this, as an energy source would attach 20% or 30% more to the prices of steel creation in the early years.

3 Methodology.

The methodology used in this research is the Sustainability Assessment Framework for Scenarios (SAFS) and the Multi-Criteria Decision Analysis. These two were used as a complement to each other, considering that both serve a very useful purpose in the paper. They were used simultaneously but separately to increase the reliability and precision regarding the plan of making the whole assessment with an holistic approach and bearing in mind the overlapping circles of sustainability.

SAFS methodology for qualitative assessment of possible scenarios originated from an environmental and social perspective, so it aims to deal with the inherent uncertainty of the implementation of the use of hydrogen from a broader perspective and it was used as an example in the doctoral thesis by Arushanyan et al., where they analysed the environmental impacts of information and communication technologies (ICT).

Once this methodology was completed, a Multi-Criteria Decision Analysis was implemented to analyse the current hydrogen production technologies, from their safeness to their costs, including social interactions and environmental friendliness.

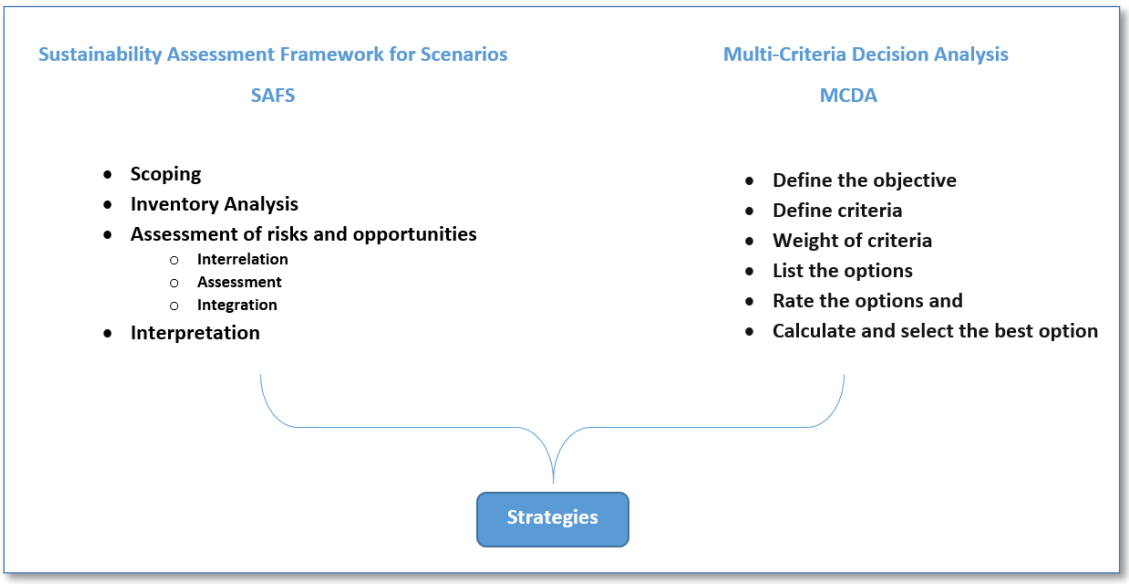
Due to the reason that the economic perspective is not included in SAFS methodology, it was decided to implement it in the second part of the MCDA, because it is a very important factor in sustainable development.

The scopes and targets of this paper differ from each other with respect to the timelines, for SAFS the evaluation was collected to analyse the future, therefore, the predicted years initiated in 2030 and finished around 2060, owing to the variance from each institution and experts forecast. In addition, it is focused on the whole hydrogen system, from production to utilisation, including transportation, markets, infrastructure, and governmental policies.

The compilation of the MCDA data was related to the technologies of hydrogen generation at the present moment in all the sustainability perspectives, including safety concerns and energy efficiencies aside from the environment, social, and economics.

Below, a figure is illustrated to visualise the combination of these two methods.

Figure 1: Combined methodology used in this paper with strategies as a complement.



However, the interrelation between both, serves as an understanding of the main objective of this paper. Visualising these two methods helps to provide an easier comprehension to the lector of how is at the moment and how will be used in the future.

Sustainability Assessment Framework for Scenarios

The main parts of this framework for scenarios are the scoping, inventory analysis, the analysis of risks and opportunities, and the interpretation of such features and elements. SAFS framework incorporates the consumption viewpoint, highlighting the significance of considering the impact on a globalised approach without border limitations (Arushanyan, Ekener, & Moberg, 2017).

As the process of creating future scenarios is identified by intrinsic unpredictability, it is a must to discuss the results in the context of ambiguity when performing an assessment with SAFS and to freely and openly disclose the assessment techniques when presenting the results with transparency.

One of the facts to highlight here is that usually during an assessment of future scenarios, exists the participation of experts to assemble their ideas and thoughts about the innovation to evaluate. A variety of techniques are usually utilised in iteration to build the structure of the SAFS. These include literature studies, conversations between members of the assessment group and the project group as a whole, workshops, and putting SAFS to the test by using it in a real-world scenario (Arushanyan, Ekener, & Moberg, 2017). Nevertheless, for this paper, miscellaneous reports were taken into account, where all these experts had already joined to talk about hydrogen. Participatory methods were used in a number of the examined assessments which provide a structure to incorporate the participation of stakeholders in evaluating sustainability impacts.

Information on the contemporaneous state of the environmental and social aspects was gathered through literature reviews and discussions with actors/stakeholders and experts, interdisciplinary, engineering, and economic, scientific knowledge, governmental documents, and reports produced by NGOs. Three scenarios were analysed, economic decline, improvements in efficiency/technology, and external events (conflicts/global warming).

SCOPING:

This assessment aims to evaluate future scenarios of European countries in the following years (~2050) associated with environmental and social risks and opportunities.

An evaluation of these scenarios can be developed by considering existing scenarios or implementing new ones. The main thought of SAFS is that the review should be possible in a close joint effort with partners. Utilising a subjective strategy (Ibáñez-Forés et al., 2014), by incorporating the examiner's perspective, outer proposals, or a board of specialists, either a hierarchical or granular view is recommended in SAFS.

A short description of the scenarios is stated below these lines:

"Economic decline" We are living in difficult and uncertain times where the economy of the world is being affected and has deteriorated during the last years due to the previous pandemic, which is deterring people's everyday lives and at the same time affecting the whole supply and demand system.

"Improvements in technological efficiency" The development of new long storage batteries, fuel cells, and, electrolysers is primordial if the main goal is to eliminate dirty energies and foster the use of clean energies. With the government policies and targets for 2050, the performance of new cutting-edge technologies is of the utmost importance.

"External events" Include disasters, conflicts among countries, biased decisions, new policies due to failed systems, and global warming side effects that could arise.

INVENTORY ANALYSIS:

Some factors were taken into consideration to evaluate the data and complement the scenarios evaluation.

The contextual factors were:

"Governance system" identifies each scenario's political system and societal structure, encompassing environmental policies and social welfare. During this sector, the government planning of possible new regulations is taken into account.

"Hydrogen maturity" refers to the development of infrastructure and the use of hydrogen by society, including privacy issues such as accessibility and affordability and some flexibility options to balance the offer and demand within the hydrogen economy.

"Value system" is based on social rules and values and depicts people's relationships and how society is affected as well as environmental participation and awareness like equity and justice.

"Industry and technology" denotes state-of-the-art technology production, exchange model (markets), and development of such technology.

ANALYSIS OF RISKS AND OPPORTUNITIES

Only direct relationships between some contextual elements and various environmental and social characteristics were contemplated in the interaction study. In this part, SAFS proposes creating new contextual features from the environmental assessment outcomes and applying them to a subsequent round of social evaluation if there are negative impacts during the first process. Some examples of these new contextual elements are access to natural resources or ecologically friendly living conditions.

INTERPRETATION:

Once the scenarios were analysed with the contextual factors, a short conclusion was made. The integration of all the sectors within sustainable development is primordial. Societal significantly impacts ecosystems, and both play a considerable role in cohabiting. That is why it is imperative to analyse the whole process and all their perspectives.

Multi-Criteria Decision Analysis

A Multi-criteria decision analysis (MCDA) is a decision-making tool that helps to simplify, analyse and evaluate multiple possibilities under diverse criteria (Pohekar & Ramachandran, 2004). The main steps of the criteria analysis are: 1) Define the objective, 2) define criteria 3) weight of criteria 4) list the options 5) rate the options, and 6) calculate and select the best option

The major motivation for integrating MCDA and SAFS stems from the need to make the hydrogen generation procedures more relevant and how the implementation of green or blue hydrogen is taking us to a more sustainable world. There are numerous assessments from innovative methodologies to increase performance and avoid as much as possible negative impacts on the environment and human health.

The field of hydrogen includes a variety of specifications that require assessment on different criteria. For instance, the decision on every project destined for the energy market requires expertise, planning, and integration of various actors such as government, stakeholders, companies, and citizens, along with the necessity to reduce costs, eliminate environmental degradation and facilitate policymaking in a democratic approach.

Generally, a sustainable strategy for any business entails a positive impact on the environment, and society, and also provides benefits to the company and shareholders. Nowadays, with the grandiose momentum that sustainability is having in our society, more and more companies are adopting the triple bottom line, which suggests that organisations should not only have economic benefits but also focus on their environmental and social impact. That approach is as well known as the three Ps encompassing people, planet, and profits. (Miller, 2020). Sustainable Business Strategy claims that there is mounting evidence that companies with strong environmental, social, and governance (ESG) indicators typically generate higher financial returns while making investments and profits in the long run.

There are plenty of paths to apply MCDA with a few variations on each of them depending on the punctuation system and usually, some have better advantages over others. They are classified into two main groups, direct and indirect. A few of these direct trade-off domains are SMART combined with swing weighing, analytic hierarchy process, and points allocation. On the contrary, within the indirect methods, can be found the discrete choice experiments or PAPRIKA which means potentially all pairwise rankings of all possible alternatives.

On one hand, sometimes, direct methods are easier because they have simple formulas that could be implemented by hand in comparison with indirect methods that have more equations and need special mathematical software. Interestingly, the direct methods allegedly have proven to be more precise than those involving decision-makers discernments (Kahneman, 2011). On the other hand, the benefit of indirect strategies is that picking between several elements is a natural characteristic of choice activity that society experiences in regular routines (Drummond, Sculpher, Claxton, Stoddart, & Torrance, 2015).

The two decision-making tools used in this paper were first, the Weighted Sum Model, which is a methodology often employed in several applications such as robotics, processing data, and many more. It is a multi-criteria process where we must choose the best option among several possibilities based on a number of criteria that the evaluator assigns according to particular specifications.

The second technique is the so-called PAPRIKA, which involves the person who makes the decision, answering a series of straightforward questions using both their expertise and personal judgment. The answer to each question is a choice between two hypothetical options that are defined by only two criteria or attributes at a time. It adjusts based on every response to each pairwise question. In light of your response and those all previous questions, PAPRIKA selects a new question for you to respond to. Another question is given depending on your response followed by another, and so on.

4 Results.

First of all, the current condition of hydrogen production techniques (grey, turquoise, green, and blue) was stated from the distinct sustainability aspects such as environmental, economic, and energy.

Afterward, the Multicriteria was implemented to follow a coherent series of details of all the colours. Later the assessment of the future scenarios was described along with the contextual factors and, finally a few strategies were suggested to avoid some side effects from the scenarios proposed.

4.1 ENVIRONMENTAL PERSPECTIVE

Some of the foundational consequences and impacts on the environment are those having detrimental effects on air, water, and soil, which in turn could become deleterious to human health. Just to mention a few of them; pollution, land use impacts, water consumption alterations, flora and fauna disruptions, et cetera. The greenhouse gases produced by hydrogen production are by far the most considerable repercussions. During its production with fossil fuels, the generation of these gases made the whole process not ecological.

Hydrogen emissions into the troposphere react with hydroxyl radicals, which induce drastic changes in the diffusion of methane and ozone and give rise to increased radiative forcing. Even though it is a secondary or indirect greenhouse gas, if not correctly managed or transported, a leakage of around 10% could add 6% to global warming (Derwent, et al., 2006).

Collecting information from few papers, we were able to ferret out the following information about efficiency from different production techniques and their impacts on the environment.

The findings are discussed further in these lines.

4.1.1 GREY HYDROGEN

Grey hydrogen represents the major pathway of hydrogen generation and releases around 9.3 kg of CO_2 per kilogram of hydrogen (Rapier, 2020).

Life Cycle Analyses of the different hydrogen generation technologies made by AlQahtani and colleagues, using ecological standardisation, models and software and having as the main target to appraise the environmental impacts on their midpoint (focus on one problem at a time) and endpoint indicators (focusing on three higher aggregation levels, on human health, ecosystems and resource depletion) The results showed that biomass gasification has the highest effect on the ecosystems due to the plantation and burning of biomass, which produces changes in land use and consumes much water. As far as human health is concerned, coal gasification had the worst impact, and the technologies with more

resource depletion were those using fossil fuels, especially natural gas as a feedstock like SMR and Methane pyrolysis (Al-Qahtani, Parkinson, Hellgardt, Shah, & Guillen-Gosalbez, 2021).

When only energy usage and process emissions are taken into account, coal gasification emits about 675 grams of carbon dioxide per kilowatt of hydrogen, whereas steam methane reforming (SMR) releases around 285 g/kWh of carbon dioxide or 9.5 kilograms of CO_2 per kilogram of hydrogen (Committee on Climate Change, 2018).

4.1.2 BLUE HYDROGEN

Using carbon capture storage for steam methane reforming diminishes the consequences on human health by 48 per cent and ecosystems by 63 per cent. In the same way with coal gasification, the improvements are notorious, at around 20% in human health and 44% in the ecosystems (Al-Qahtani, Parkinson, Hellgardt, Shah, & Guillen-Gosalbez, 2021).

However, there are still some environmental concerns associated with CCS that can be divided into two categories: local risks owing to high, localised concentrations of CO_2 as a result of leakage; and global risks stemming from low carbon dioxide levels that slowly go back into the atmosphere over time. Water pollution is one of the greatest and pivotal environmental issues facing the community today. As a consequence, aquatic plants and other life forms that rely on groundwater as a source of drinking water would be adversely affected by such water supply contamination. That poisoning can be fatal to plants and animal's life when exposed in concentrated doses. Corrective mechanisms for the remediation of contaminated aquifers are available, but stopping the leakage before entering the aquifer is crucial. Those technologies are usually quite expensive (IPPC , 2005).

4.1.3 TURQUOISE HYDROGEN

During the production of hydrogen from Methane Pyrolysis, there are no carbon dioxide emissions to the atmosphere; however, some emissions are released from the electricity used during the extraction and transportation of the natural gas, mainly from the sweetening of natural gas and the leakages from methane (Sánchez-Bastardo, Schlögl, & Ruland, 2021).

4.1.4 GREEN HYDROGEN

An environmental impact assessment of three electrolysers (Alkaline, Polymer Electrolyte Membrane, and Solid Oxide) by life cycle analysis from cradle to gate was conducted by Camilla Sunden from KTH University. It concluded that the polymer electrolyte membrane electrolyser has the lowest environmental impact, but their efficiency, in general, is influenced significantly by their lifetime and density (Sundin, 2019).

One assessment carried out by Koj et al. showed that the building of the alkaline electrolyser has the highest impact on ozone depletion potential. Nevertheless, the operation stage occupies the worst environmental influence on electricity supply (Koj, Wulf, Schreiber, & Zapp, 2017). A potential method for alkaline electrolysers to make these cells lighter and smaller while also preventing KOH leakage is anion-conducting membranes (Bodner, Hofer, & Hacker, 2015).

An examination of different green hydrogen production techniques from electrolysis run with renewable energy sources such as solar (photovoltaic and thermal), wind, hydro, and biomass and checking on some environmental issues such as eutrophication, acidification, and global warming potential, showed that electrolysis run with photovoltaic (PV) energy has the worst environmental effects due to the production of the PV panels (Sundin, 2019). The carbon footprint emission from PV systems was determined to be in

the region of 14 and 73 g CO_2/kWh, which is far less than the emissions from fossil fuels production at 742 g CO_2 /kWh (Tawalbeh, et al., 2021).

4.2 ENERGY PERSPECTIVE

Approximately 120 Mt of hydrogen is generated annually in the world today, with 2/3 of that being pure hydrogen and 1/3 a combination of hydrogen and other gases. According to data from the International Energy Agency, this amounts to 14.4 exajoules (EJ), which is equal to 4000 TWh and represents around 4% of the world's total final energy (IEA, 2019).

4.2.1 GREY HYDROGEN

SMR has the highest energy efficiency at around 75 per cent among all the processes where carbon sources are utilised but it also achieves higher heating values of up to 85%. During Steam Methane Reforming the energy required to produce one mole of hydrogen is 63.3 kJ/mol H. Coal gasification efficacy oscillates around 60%; partial oxidation and autothermal reforming create the same efficiencies, something between 65 and 75% (El-Shafie, Kambara, & Hayakawa, 2019).

The gasification is divided into two processes in light of the feedstock utilised for hydrogen creation; biomass and coal gasification. From these two, biomass gasification is the most attractive technique for hydrogen production. During biomass gasification, the feedstock is partially oxidised at higher temperature ranges between 800 and 900 °C (Kannah, et al., 2021).

4.2.2 BLUE HYDROGEN

As was mentioned beforehand, SMR has an outstanding efficiency without any CCS, nonetheless with the addition of this technology to avoid gas emissions, its efficiency plummets to 60% or even lower due to the excessive energy consumption used. The efficiency of coal gasification with CCS at a lower heating value is 58% (IEA, 2020).

4.2.3 TURQUOISE HYDROGEN

Related to the Enthalpy reaction, 37.7 kJ is required in methane pyrolysis to obtain one mole of hydrogen (Abbas2010). This method uses a smaller amount of energy than green hydrogen techniques of up to 4 times lower, and around 20% lower than SMR; however, the efficiency of methane pyrolysis is approximately 58%. (Steinberg, 1998).

4.2.4 GREEN HYDROGEN

At the moment, commercial electrolysers are offered in capacities up to 10 MW and their efficiencies vary between 50 and 80 per cent. The amount of energy contained in one kilogram of hydrogen is approximately 40 kWh/kg, and to produce 1 kilogram of hydrogen, they need between 50 and 80 kWh of solar power (Lipták, 2022).

PEM electrolysers have certain advantages, such as superior flexibility and an easier way to couple with intermittent systems such as solar and wind, attaining an efficiency as high as 85% and the purity of the hydrogen produced by these polymer membranes is very high (Goetz2016). Furthermore, they don't have issues with corrosion and seals like Solid Oxide Electrolysis Cells and have a better electricity output than Alkaline electrolysis (Wang, 2012).

The total necessary energy to produce one mole of hydrogen during the water electrolysis is 285.8 Kj without taking into consideration its evaporation (Kumar & Himabindu, 2019).

Based on an Irena analysis in 2020, the different efficiencies from the current electrolysis techniques are as follows: Alkaline electrolysis performance is found from 50 to 78%, Proton Exchange Membrane (PEM) electrolysis fluctuates around 47% and 85%, Anion Exchange Membrane efficiency is roughly 57 and 69 per cent and Solid Oxide Electrolysers effectiveness stands at around 45% and 55% (IRENA, 2020).

4.3 ECONOMIC PERSPECTIVE:

To thoroughly analyse the main costs of this technology is necessary to include different elements that could add to or reduce expenses. The levelised cost of hydrogen (LCOH) comprehends capital and operational expenditures, materials, storage methods, transportation, delivery, conversion, application, market values, and electricity prices during its production. But efficiency, plant size, capacity factors, and external components aggregate a particular value of the costs (Hartley, et al., 2019). Currently, transportation by ships fluctuates between 6.5 dollars per kg and 17.3/kg, depending on the distance during the shipping (IRENA, 2022b).

Depending on the kind of technology used to produce hydrogen, the costs vary because the manufacturing employed is diverse. Hereinafter the current costs and possible future outgoings are going to be highlighted according to a couple of sources from scientific and governmental papers.

According to Bloomberg New Energy Finance, some African, European, and Middle Eastern countries already pay less for green hydrogen compared to grey. Their analysis states that one kilogram of grey hydrogen at present values $6.71 in these areas versus green hydrogen hovering around $4.84 to $6.68 per kilogram. Using a statistical model, they predicted that grey hydrogen without carbon capture storage will be more costly than green hydrogen by 2030 (NEF, 2020).

4.3.1 GREY HYDROGEN HYDROGEN

Nowadays, the price of grey hydrogen is the cheapest form within the production paths around the world. The International Energy Agency (also known as IEA) declares that hydrogen produced the fossil fuels costs around 1.5 euros per kilogram or 0.045 euros per kWh. Another source states that the cost for one ton of hydrogen produced using SMR is 2000 euros or 2 euros per kg (Sánchez-Bastardo, Schlögl, & Ruland, 2021). The price for Steam Methane Reforming hovers between 0.7 and 1.6 dollars per kilogram (IEA, 2020)

The expenditures for coal gasification are predominantly dependent on the investment (Capex), and it is the cheapest technology for the whole product generation of hydrogen, including fixed costs, raw material, and energy, followed by SMR with the only difference that the primary expenses are affected by the price of natural gas (Machhammer, Bode, & Hormuth, 2016). According to a report called Hydrogen in a low carbon economy, the prices for coal gasification could change to £12/MWh by 2050, depending on coal price foresight (Committee on Climate Change, 2018). As stated in a research paper written by Al-Qahtani and colleagues, the most feasible alternative from an economic perspective is steam methane reforming with carbon capture and storage (Al-Qahtani, Parkinson, Hellgardt, Shah, & Guillen-Gosalbez, 2021).

4.3.2 BLUE HYDROGEN

The costs of blue hydrogen are a bit higher when Carbon Capture Storage is implemented, but the benefits overweight the adverse effects. Carbon sequestration entails a few steps such as capture, pressurisation, transportation, and injection of liquefied carbon dioxide underground (geological

formations, salt caverns, oil wells, or natural gas fields) or beneath the ocean. According to some estimates, the latter is doubly more expensive than the first one, and all the procedures related are highly demanding in energy and costly (Okken, 1993) and the catch and removal of this CO_2 add around 25-30% to the expense of hydrogen delivered by SMR. (Audus, Kaarstad, & & Kowal, 1996).

During these days the cost of blue hydrogen varies depending on the production technology. The cheapest hydrogen costs $1.69 per kg, but the most expensive hydrogen costs $2.55 per kg. There are three different ways to create hydrogen: using autothermal reforming (ATR), carbon capture and storage (CCS), and natural gas decomposition with CCS. The three methods have different costs, with ATR being the cheapest and natural gas decomposition with CCS being the most expensive (Oni, Anaya, Giwa, Lullo, & Kumar, 2022).

And according to the International Energy Agency, Coal Gasification production with CCS is estimated to be 2.3 USD per kilogram of hydrogen. Steam Methane Reforming with Carbon Storage costs are around $1.6/kg (IEA, 2020).

3.3.2 TURQUOISE HYDROGEN HYDROGEN

The price for this technology using methane pyrolysis strongly relies on the processing route, the cost of natural gas, and the solid carbon produced during the process (Parkinson, et al, 2019), but also on the gas, the kind of catalysts, temperature and residence time (Demirbaş, 2001). The net outlay to produce one kilogram of hydrogen varies from 2.6 to 3.2 euros. The products of methane pyrolysis are carbon and hydrogen, making carbon sequestration a bit easier. On the other hand, solid products such as carbon black, carbon fibres, and carbon nanotubes have several useful employments, and they are economically worth the markets. In addition, this could offset the costs of H_2 production using this methodology (Sánchez-Bastardo, Schlögl, & Ruland, 2021).

A couple pyrolysis choices become competitive with expanding carbon dioxide levies (Parkinson, Matthews, McConnaughy, Upham, & McFarland, 2017). A comparative study of the costs between biomass and methane pyrolysis made by Nikolaidis and Poullikkas came to the conclusion that CH_4 pyrolysis is more expensive than biomass pyrolysis, with 1.25-2.2 dollars per kilogram of hydrogen compared to 1.77 - 2.05 USD respectively (Nikolaidis & Poullikkas, 2017). In an older bibliography, it is observed that was more expensive before than now, hereBartels shows that the costs per kilogram of hydrogen use for feedstock are 2.57 dollars (Bartels, Pate, & Olson, 2010).

4.3.3 GREEN HYDROGEN

Electrolysers will be the most important source of hydrogen in the future due to their zero greenhouse gas emissions and byproducts like electricity, and heat. However, the production costs must be reduced drastically to be competitive with other carbon-based mechanisms. As it was stated before in this document, alkaline electrolysis (AE) is the most commercial and mature technique for electrochemical production and has lower capital costs than the other techniques. Proton exchange membrane (PEM) electrolyser has a greater variety of advantages compared to AE. This covers a smaller portion of the footprint and a more rapid dynamic response time that is technically a better option for coupling renewable energies into different sectors. Levelised costs from AE and PEM hover at 4.78-5.84 and 6.08-7.43 dollars respectively, according to the National Hydrogen Roadmap (Bruce S, 2018). Solid oxide electrolysis cells (SOECs) are a less mature technology but have the potential to increase efficiency levels up to 8o per cent.

The most notorious element of green hydrogen production is the power supply (electricity) cost, representing around 30% of the total. Nevertheless, the potential for cost reductions is high and it can be achieved by cutting down the electricity. The second major cost is the electrolysis facilities. A case in point is that escalating the size of the plant from 1 MW to 20 MW would diminish the value by up to one-third (IRENA, 2020).

Minimising the materials costs and increasing control systems and standardised procedures could reduce investment expenses for AE batteries by 30 or 40 per cent and scale-up productions from 50 to 1,000 units per year will plummet the CAPEX of the balance plant section by 20 or 30 per cent. On the other hand, (Ludwig, et al., 2022; Ludwig, et al., 2022). Green hydrogen production utilises water as a key feedstock to separate hydrogen and oxygen from water. Water consumption using PV, ranges between 22 and 126 kg of water per 1kg of hydrogen, depending on diverse factors (IRENA, 2020). Water is essential for the electrolyser performance, and they require it to be as pure as possible due to the reason that impurity impacts the lifetime of the electrolyser stack; Notwithstanding, the cost of water purification is marginal and it generates a low impact on the overall cost of hydrogen, around 0.01 USD/kg H2 (Hand, Guest, & Cusick, 2019).

The BloombergNEF in its paper Hydrogen Economy Outlook predicted for the year 2030 that the global industry will be able to deliver hydrogen for a benchmark cost of $2/kg and $1/kg in 2050 in various countries around the globe (NEF, 2020) Aurora forecasted by 2025 that the costs for green hydrogen production would be around €5/Kg.

4.4 INVENTORY ANALYSIS:

Hereinafter, the suggested scenarios associated with the contextual factors expressed previously in the methodology were described, and a table was implemented as a visual support.

The details described in the table below were obtained from scientific papers, reports, and governmental and private institutions. Information also reached from knowledge attained from some classes and modules, accompanied by social media and news.

Table 1: Proposed scenarios compared to the contextual factors

CONTEXTUAL FACTORS	***Scenario: Economic decline***	***Scenario: Technological Improvements***	***Scenario: External events***
Governance System	Decrease taxes and levies to help citizens Implementation of supporting schemes and incentives	Increase funding in R&D for more novel H_2 technologies. Create more agreements with more companies and governments.	Could generate shifts in political relationships with other countries Policies could be modified in case of sanctions on other countries.
Hydrogen Maturity (Flexibility options)	Infrastructure for new pipelines could be delayed. Very limited storage infrastructure	Curtailment can be diminished by up to 30%. A balance between buying electricity when	Electrolysers may be employed in locations where the energy is generated from intermittent renewable sources and where the

	Renewable energy prices will probably remain and not be affected. Fewer opportunities for gas or hydrogen imports Lower investment expenditures on logistics, installation, and batteries	prices are low and increasing the utilisation of electrolysers. Accelerate and intensify renewable energy deployment and start getting more competitive. More use of renewable energies in households. The yearly demand for hydrogen will augment. Expansion of hydrogen networks. Two-thirds of green hydrogen production in 2050 will be used regionally and 1/3 will be traded across countries.	extra energy cannot be stored in batteries or delivered over power lines. Industrial and residential relocations due to natural disasters. Hydrogen facilities located in coastal regions will be vulnerable to the effects of climate change, such as storms, flooding, and droughts.
Value System	Less willingness to pay taxes and to take flexibility options.	Lower consumer bills Creation of job positions and employment	Higher gas prices would increase the costs of renewable electricity and also bills for tenants.
Industry and Technology	Existing importation dependencies may remain or grow. In a climate of rising financing costs and increased competition, the technological companies lose profits and therefore reduce budgets for hydrogen devices (cell fuels, batteries, Pv panels) or storage developments.	Less hydrogen will be needed for the power sector. Increase the profitability of new electrolysers and long storage batteries in the market sector. Hydrogen fuel cells are enhanced for aircraft and ships and hydrogen fuel cell vehicles emit only water. More terrestrial transportation uses hydrogen as a source of fuel. Scale up of renewable power. The yearly demand for hydrogen will augment	Leakage of ammonia or other byproducts into the ecosystems. In case of conflicts, a combination of fuels, including green hydrogen might increase price stability in industries like fertilisers, aircraft, and marine commerce. One of the aftermaths of the war is the reduction of natural gas in Europe. Supply disruptions could hinder political ambitions for the climate agenda.

The inventory analysis revealed that certain information could not be supplied in sufficient depth regarding the social and environmental aspects.

4.5 ASSESSMENT OF RISKS AND OPPORTUNITIES

The interaction between the contextual factors with the environmental impacts and social aspects was considered, however, not all of them apply to each sector corresponding to every scenario proposed, so it had to be narrowed down to analyse the potential effects. The environmental features that were assessed here, included only energy, ecosystem alterations, and greenhouse gas emissions and the social aspects encompassed public participation and the influence of society.

Table 2:Interrelations between environmental and social aspects with the contextual factors

Contextual Factors	**Environmental aspects**	**Social aspects**
	Energy/ecosystems/GHG emissions	Public Participation / Influence on society
Governance system	Yes / No	Yes
Hydrogen maturity	No	Yes
Value System	No	Yes
Industry and technology	Yes	No

The assignment of Yes and No from the interrelations described in the beforementioned table was due to the reason that some papers did not have predictions for those specific aspects, although there is always participation of all actors and factors in every area or sector. Moreover, social and environmental aspects are intrinsically intertwined because we cohabit in the same ecosystem, thus, every decision taken by humans will have an impact on nature.

The bibliography used to get the information from the environmental and social aspects is shown below.

Table 3: Bibliography used to obtain the interrelations from Table 2

Contextual Factors	**Environmental aspects**	**Social aspects**
	Energy/ecosystems/GHG emissions	Public Participation / Influence on society
Governance system	(Daioglou, Mikropoulos, Gernaat, & van Vuuren, 2022)	(Kemp, 2000) (Samson, 2016) (IRENA, 2022) (Palm & Hansson, 2006)
Hydrogen maturity	No interrelations found	(Espegren, Damman, Pisciella, Graabak, & Tomasgard, 2021) (World Future Council, 2021) (Bögel, Upham, Shahrokni, & Kordas, 2021) (Lam, Fuse, & Shimizu, 2019) (Hartley, et al., 2019) (Kemp, 2000) (Lipták, 2022) (Lennon, Dunphy, & Sanvicente, 2019)

		(Fraunhofer Institute for Systems and Innovation Research, 2020) (Jones, 2022) (Ajibade & Siders, 2021) (FAO, 2022) (United Nations, 2020)
Value System	No interrelations found	(World Future Council, 2021) (Hawk, 2021) (IRENA, 2022)
Industry and technology	(Tseng, Lee, & Friley, 2005) (Polaiah, 2018) (Fraunhofer Institute for Systems and Innovation Research, 2020) (AURORA, 2022) (Hartley, et al., 2019) (Sinn, 2017) (IRENA, 2018b) (IRENA, 2016b) (Orozco, et al., 2019) (Ocko & Hamburg, 2022) (Polaiah, 2018)	No interrelations found (Although development in the industry sector could affect employment rates in fossil fuel sectors)

Once some interrelations were discovered, every one of those contextual factors was evaluated for each scenario in order to elucidate the possible effects either negative or positive.

Each of these interrelations was dissected to characterise the possible impacts of each contextual factor. The probable impacts of each interrelation on every aspect were determined using data gathered from the literature, reports, websites, and information on the contextual elements acquired through the scenarios (View Table 1).

4.5.1 ENVIRONMENTAL IMPACTS

Table 4: Results from the interrelation assessment for potential effects on environmental aspects in the scenario "economic decline "

Economic decline scenario		
Contextual factor	**Information derived from the scenario**	**Potential effects on environmental aspects (energy/ecosystems/gas emissions)**
Governance System	Decrease taxes and levies in order to help citizens. Implementation of supporting schemes and incentives.	It does not apply It does not apply
Industry and technology	Depending on the country,	Hydrogen transportation generally over long distances requires high

	existing importation dependencies may remain or grow. Technological evolution might be affected because other issues are prioritised In a climate of rising financing costs and increased competition, the technological companies lose profits and therefore reduce budgets for hydrogen devices (cell fuels, batteries, Pv panels) or storage developments.	energy density (Fraunhofer Institute for Systems and Innovation Research, 2020). Heterogeneity could create energy security (Tseng, Lee, & Friley, 2005). Some of the environmental problems come as a result of technology mismanagement by creators and consumers (Polaiah, 2018) Assumption: Without or with slow-pace improvements in technology, the energy losses remain high as well as the impacts on the environment from the main components.

Table 5: Results from the interrelation assessment for potential effects on environmental aspects in the scenario "technological improvement scenario "

Technological Improvement scenario		
Contextual factor	**Information derived from the scenario**	**Potential effects on environmental aspects (energy/ecosystems/gas emissions)**
Governance system	Increase funding in R&D for more novel H_2 technologies. Create more agreements with more companies and governments.	They pave the path for new developments that could reduce energy consumption, carbon dioxide emissions, and side effects on the ecosystems. At the end of the century, the creation of novel technologies could diminish the global energy demand by 60 per cent (Daioglou, Mikropoulos, Gernaat, & van Vuuren, 2022).
Industry and technology	Less hydrogen will be needed for the power sector after 2040. Increase the profitability of new electrolysers and long storage batteries in the market sector.	Around 13% less hydrogen energy will be needed until 2050 for the power sector (AURORA, 2022). Projects will be implemented by 2040 at around 213.5 gigawatts, which in turn, will reduce the electricity produced by fossil fuel plants, and the depletion of CO_2 emissions (AURORA, 2022).

	Hydrogen fuel cells are enhanced for aircraft and ships and hydrogen fuel cell vehicles emit only water.	Airplanes are assumed to have an 8% reduction in energy consumption. No gas emissions to the atmosphere (Sinn, 2017).
	More terrestrial, aerial, and maritime transportation uses hydrogen as a source of fuel.	5% of all buses in Europe are estimated to function with hydrogen and 55% of trucks. By 2040, 35% of vehicles will be fueled with hydrogen and 44.8 g/km of CO_2 will be reduced (Analysing future demand, supply, and transport of hydrogen). Less noise, and less water pollution, trains lessen noise and wipe out local emanations, passengers appreciate the reduced local emissions and water pollution. (Hartley, et al., 2019)
	Scale up of renewable power	By 2030, new cooling methods and the combination of photovoltaic panels and wind power generation might cut the amount of water needed to produce energy by 42% and 84%, respectively (IRENA, 2016b) (IRENA, 2018b).
	The yearly demand for hydrogen will augment.	It will increase around 7 times (Orozco, et al., 2019).

Table 6: Results from the interrelation assessment for potential effects on environmental aspects in the scenario "external events"

External Events		
Contextual factor	**Information derived from the scenario**	**Potential effects on environmental aspects (energy/ecosystems/gas emissions)**
Governance system	Could generate shifts in political relationships with other countries	It doesn`t apply
	Policies could be modified in case of sanctions on other countries.	It doesn`t apply
Industry and technology	Leakage of ammonia, hydrogen, or other byproducts into the ecosystems.	Ammonia can have detrimental effects on individuals and ecosystems (Orozco, et al., 2019).

		In the event of a high percentage of H2 leakages ~10 %, and with projections of achieving 20% of the total energy demand by 2050 it could increase global warming between 0.06 and 0.01 degrees (IEA, 2021). Blue hydrogen with high leakages may be worse for the environment than fossil fuels technologies, generating up to 60 % more warming during the first decade and taking 50 years before seeing the benefits, based on GWP-100-derived evaluations (Ocko & Hamburg, 2022).
	In case of conflicts, a combination of fuels including green hydrogen might increase price stability in industries like fertilisers, aircraft, and marine commerce.	While trying to control a price balance within the industry sector, it will enable the current climate goals to be achieved without alternating anything related to the environment (Hartley, et al., 2019).
	One of the aftermaths of the war is the reduction of natural gas in Europe.	In the energy sector, the costs of renewable energies would rise by 40% and the electricity prices also would increase (AURORA, 2022)
	Supply disruptions could hinder political ambitions for the climate agenda.	Policymaker may change their focus on other technologies fostering the energy transition (IRENA, 2020), and with that other gas emissions and energy predictions could emerge.

4.5.2 SOCIAL IMPACTS

Table 7: Results from the interrelation assessment for potential effects on social aspects in the scenario "economic decline"

Economic decline scenario		
Contextual factor	**Information derived from the scenario**	**Potential effects either positive or negative on societal aspects**
Governance system	Decrease taxes and levies to help citizens.	There is a chance that indirect economic stimuli, like taxes and

	Implementation of supporting schemes and incentives.	subsidies, will be inadequate or weak (Kemp, 2000). Implementation of incentives might alter people's behavior. (Samson, 2016).
Hydrogen maturity	Infrastructure for new pipelines could be delayed. Very limited storage infrastructure. Renewable energy prices will probably remain and not be affected. Few opportunities for gas or hydrogen imports. Lower investment expenditures on logistics, installation, and batteries.	Energy problems within the community (World Future Council, 2021) Citizens' trust is affected by delays and they won't trust anymore in contractors or institutions (Malhotra, 2014). It doesn't apply. Unemployment rates increase in the oil sector (Espegren, Damman, Pisciella, Graabak, & Tomasgard, 2021). Risk factors ramp up and with that human incidents (Lam, Fuse, & Shimizu, 2019).
Value System	Less willingness to pay taxes and to take flexibility options.	Current financial instruments should be straightened, especially in the promotion of local businesses or communities (World Future Council, 2021).

Table 8: Results from the interrelation assessment for potential effects on social aspects in the scenario "technological improvements"

Technological Improvements		
Contextual factor	**Information derived from the scenario**	**Potential effects either positive or negative on society**
Governance system	Increase funding in R&D for more novel H_2 technologies. Create more agreements with more companies, researchers, and governments.	Decrease the investment risk for industry and market (IRENA, Geopolitics of the Energy Transformation, 2022). This would allow efforts from other sectors of society, including universities to be directed toward analysing and making people more aware of hydrogen.

		(IRENA, Geopolitics of the Energy Transformation, 2022).
Hydrogen maturity	Curtailment can be diminished by up to 30%. Creates a balance between buying electricity when prices are low and increasing the utilisation of electrolysers. Accelerate and intensify renewable energy deployment and start getting more competitive. More use of renewable energies in households. Expansion of hydrogen networks. Two-thirds of green hydrogen production in 2050 will be used regionally and 1/3 will be traded across countries.	Assumptions are that prosumers and consumers have a passive role which in the end, it is not relevant (Bögel, Upham, Shahrokni, & Kordas, 2021) Demand-side management is an appealing strategy to incentivise consumers to use energy efficiently (Bögel, Upham, Shahrokni, & Kordas, 2021) Local economic development and increased employment prospects for nearby communities (World Future Council, 2021). Communities are motivated to participate in peer-to-peer systems, nevertheless, they should have the proper financial support and energy justice by enabling them to participate in the design projects (Lennon, Dunphy, & Sanvicente, 2019). The increase in hydrogen and fuel cell economy in Europe would create around 38,500 direct jobs and nearly 70,000 indirect jobs in euros by 2030 (Fraunhofer Institute for Systems and Innovation Research, 2020) Land use will be a social acceptance issue (Kemp, 2000). New distribution networks are likely to be regionalised (Jones, 2022).
Value System	Lower consumer bills Creation of job positions and employment	Assumption: People's satisfaction increases The hydrogen industry would employ around 1 million people in 2030 (Hartley, et al., 2019)

Table 9: Results from the interrelation assessment for potential effects on social aspects in the scenario "external events"

External Events		
Contextual factor	**Information derived from the scenario**	**Potential effects either positive or negative on society**
Governance system	Could generate shifts in political relationships with other countries Policies could be modified in case of sanctions on other countries.	Society tends to take time to assimilate new policies (Palm & Hansson, 2006). Assumption: Citizens could be affected.
Hydrogen maturity	Electrolysers may be employed in locations where the energy is generated from intermittent renewable sources and where the extra energy cannot be stored in batteries or delivered over power lines. Industrial and residential relocations due to natural disasters. Hydrogen facilities, located in coastal regions, will be vulnerable to the effects of climate change, such as storms, flooding, and droughts.	Effects on land use changes, water scarcity (FAO, 2022). Low levels of social acceptance (World Future Council, 2021). Relocation contributes to inequality and demoralisation and also affects the community`s heritage and livelihoods. It also has sentimental values (Ajibade & Siders, 2021). Imbalance in the gas sector and residential mobility usually tends to lead to poor health conditions and children's problems (Jones, 2022). Forced resettlement and without adequate compensation (United Nations, 2020).
Value System	Higher gas prices would increase the costs of renewable electricity and also bills for tenants.	Scarcity of basic needs due to the reason that food and gasoline will raise their prices, which for some people will become uneconomic (Hawk, 2021). Human security is affected (IRENA, Geopolitics of the Energy Transformation, 2022)

Since there were not many studies related to some scenarios, some assumptions had to be made. On the other hand, some information derived from the scenarios did not apply to specific aspects either of the environment or society.

For instance, to portray the impact of the contextual factor "Value System" on the perspective of "Social aspects" in the "Technological improvement scenario" or for the contextual factor "Industry and Technology" for the potential effects on the environment" in the "economic decline scenario " the

assumptions were made from my perception on historical occurrences in a daily basis applied to those cases.

4.6 INTERPRETATION

From the results of the intertwined analysis of all contextual factors and scenarios across the environmental and social perspectives, it can be summarised that from the whole literature review some studies are not highly developed such as future scenarios in case of catastrophic events on the hydrogen topic. Here some ideas were proposed to make clear that there are always possibilities of certain events could happen and how citizens and governments should be prepared in order to tackle the side effects. Few assumptions were made for the potential effects either on social or environmental sectors or some were taken from different literature reviews not related to future scenarios of hydrogen due to the lack of those.

Although, for the scenario of external events, not only is the energy disrupted by natural disasters or conflicts among countries, but also from human errors, technical failures, or other types of disturbances that could happen when governments endeavour to use energy exchange and reliance as a coercive device for geopolitical purposes. There are numerous authentic cases when countries control energy streams such as trade blacklists or import boycotts, energy costs by limiting their partners, or within the energy framework when fabricating new oil and gas pipelines to accomplish international strategy objectives (Van de Graaf, Thijs and Sovacool, Benjamin K., 2020).

These interpretations are just a brief summary of several scenarios that could occur in the event of such disruptions either in the economy, technology developments, or external events. Nevertheless, for the evaluation of new technologies, the complete analysis of their implementation is of the utmost importance for society and ecosystems to reduce the possible consequences.

4.7 MULTICRITERIA ANALYSIS

Finally, after the previous evaluation and predictions of possible events, the MCDA Performance Matrix to weigh up the pros and cons was constructed.

For this MCDA three evaluations were made; 1) Assigning the same weight to every criterion, considering that each aspect is as important as the others. 2) Weighted criteria are taken from a survey by IRENA. 3) Attributing my own perspective using the software 1000minds.

The reason why the first two were analysed with a distinct methodology is that the PAPRIKA technique assigns the values to every criterion according to the answers that the examiner gives to the questions that the software displays on the screen.

The methodology used was the weighted-sum model or as well known as the points system which is a similar representation of linear equations. The PAPRIKA technique includes the answers of the decision makers by a progression of straightforward pairwise ranking questions, including picking between two speculative options or even more trade-offs. This method elaborates figures, graphs, and statistics with an online software called 1000 minds.

The goal is to obtain a better understanding of the different colour classification techniques that were selected for this evaluation (grey, blue, turquoise, and green) and from the plethora of articles come up with a table with the most important factors from the sustainability perspective.

1) The criteria valuation is always a bit complex, and tricky to determine which factor from the sustainability milieu is more crucial for the implementation of this technology, but, be that as it may, reading some papers the values of the weights were unbiasedly distributed.
2) Define objective: To find the best methodology which gives higher value nowadays to the environment and society.
3) The criteria used for this essay were; Energy efficiency, safety, cost-effectiveness, environmentally friendly, and social problems.
4) During the weighting criteria, was determined that the most unbiased rating would be to assign the same percentage of 20% to every category. This was decided because for new technologies it is important to consider every aspect where everybody is involved. The relevance of importance is the same for all the criteria,

The valuations used were given according to different literature reviews. In order to give the rates, it was decided to assign 5 values for each category in which the number 5 is the best scenario and the number 1 the worst. The five level classification was done to make the data a bit more precise and significant.

5) They were described as follows:

Energy efficiency: (Very low, Low, Medium, High, and Very high)

Safety: (Very low, Low, Medium, High, and Very high)

Costs: (Very cheap, Cheap, Normal, Expensive, and Very expensive)

Environmentally friendly: (Not friendly, Low, Medium, High, and Very friendly)

Social problems: (No problems, Low, Medium, High, and Very high)

The results from the analysis were derived from several literature reviews that were not older than 5 years of being written. The main technologies available in the market nowadays for hydrogen generation were included in the study and as it is known, every technique has its uniqueness and methodology along with all the materials that can be used to keep the technology working. That is the reason why all of them were aggregated and combined to obtain the average either on efficiency or costs.

Trying to evaluate the other factors such as social problems, safety, and environmentally friendly is a bit different, thus the proper manner to rate them was to check the life cycle assessment of hydrogen production from cradle to grave related to each production methodology.

A depictive table with the three assessments is presented below.

Table 10: Different criteria for the three Multi-Criteria Decision Analyses.

	Evaluation 1 SAME WEIGHT	Evaluation 2 IRENA SURVEY	Evaluation 3 PAPRIKA
Weight of criteria	20%,20%,20%,20%,20%	30% social problems, 25% costs, 20% efficiency, 15% safety, and 10 % environment. Taken from data by (IRENA, 2021)	Efficiency: 28.6 % Safety: 20.4 Costs: 20.4% Environmentally friendly 16.3 % Social problems: 14.3 % Percentages assigned from hypothetical questions

4.7.1 FIRST EVALUATION (Same weight for each criterion)

Table 11: Rank for each criterion according to the hydrogen generation process. The numbers mean the level from each valuation, 5 is the best possibility, and 1 is the worst.

Hydrogen production colour	Social problems	Safety	Costs	Energy efficiency	Environmentally friendly
Grey hydrogen	Very High [1]	Low [2]	Very cheap [5]	High [4]	Very Low [1]
Blue hydrogen	Medium [3]	Low [2]	Cheap [4]	Low [2]	Medium [3]
Turquoise hydrogen	Medium [3]	Medium [3]	Cheap [4]	Low [2]	Medium [3]
Green hydrogen	Low [4]	Medium [3]	Expensive [2]	Medium [3]	High [4]

To get the final results, each value that was assigned to each area was multiplied by the weighting criteria of 0.20 and then sum all of them per each technique to get a total average score.

The results illustrate that in the evaluation of all categories the best technology is green hydrogen and the worst, grey hydrogen.

Table 12: Results from the first MCDA for every H2 generation process.

	Grey hydrogen	*Blue hydrogen*	*Turquoise hydrogen*	*Green hydrogen*
Efficiency 20%	0.8	0.4	0.4	0.6
Safety 20%	0.4	0.4	0.6	0.6
Costs 20%	1	0.8	0.8	0.4
Environment 20%	0.2	0.6	0.6	0.8
Social Problems 20%	0.2	0.6	0.6	0.8
Sum	2.6	2.8	3	**3.2**

It can be observed that Green hydrogen has the highest value and grey hydrogen has the lowest.

Table 13: Average score for each hydrogen production technique from the Multi-criteria evaluation.

Hydrogen Production Technique	Rank	Score	
Grey Hydrogen	4	50%	WORST
Blue Hydrogen	3	56.7%	-
Turquoise hydrogen	2	63.3%	-
Green hydrogen	1	66.7%	BEST

Some points to stand out during the evaluation of these grades are:

Although blue hydrogen has fewer environmental impacts than grey hydrogen related to greenhouse emissions, it also has some side effects when the carbon dioxide sequestration increases, because that elevates the contributions of methane within the supply chain. Recent studies have bespoken that methane emissions surge during manufacture, processing, transportation, and delivery. The integration of CH4 emissions into a blue hydrogen life cycle analysis in a contextual manner is not insignificant and has to be outdated in the inventories and not underestimate those emissions, which compensate for the reductions from the integration of CCS (Bartels, Pate, & Olson, 2010).

Obtaining efficiencies from different sources for all the hydrogen generation techniques, it was necessary to arrange the methodologies and subsequently sum all of them and get one final average. The average for both values was rounded to a complete digit. It is important to highlight that was complicated to find a value for Autothermal Reforming and Partial Oxidation with CCS, therefore, it was conjectured a reduction of 20% from the total efficiency for the reason that the equipment used in CCS consumes around 25 per cent of the energy generated in the power plant. Consequently, the results are described in the tables in the appendix.

The rating for social impacts considered how hydrogen as a carrier of energy can affect society in many ways, such as influence, justice, equity, and conflicts on human values. The grading for safety included how the manufacturing processes and equipment affect health conditions. It was assumed to be low for blue and grey because usually, the thermochemical cycles during these processes tend to use hazardous materials and chemicals (Hydrogen Portal, 2022).

The gathered results provided from the evaluation of the different papers which are stated in Appendix sector 8.2 are the following:

Grey hydrogen: 69%
Blue hydrogen: 57%
Turquoise hydrogen: 49%
Green hydrogen: 61%

The valuation of the cost for every colour category is:

Grey hydrogen: 1.27 USD per kg
Blue hydrogen: 1.95 USD per kg
Turquoise hydrogen: 1.77 USD per kg
Green hydrogen: 5 USD per kg

4.7.2 SECOND EVALUATION (Criteria taken from IRENA survey)

To achieve a more profound knowledge of these technologies from the geopolitical point of view and how different actors believe, a Multi analysis was also done, but this time, with the support from the survey elaborated by IRENA which represented the collaboration of 164 experts and many countries. A variety of the respondents was attempted in order to distribute them in terms of backgrounds and sectors.

According to one of the questions in the survey on how important are the drivers for the national hydrogen policies and strategies and how important are the hindrances to developing hydrogen strategies, the results showed that according to our criteria analysis, the social impacts are at the top of importance followed by economic growth, efficiency, safety consideration, and environment.

Therefore, there were assigned rates of 30% to social problems, 25% to costs, 20% to efficiency, 15% to safety, and 10 % to the environment with a total sum of 100 per cent.

In the table below, it is observed the relative importance of each criterion. The values are resulted from dividing the left weights by the top weights.

Table 14: Relative Importance: Based on the mean weights, each number represents the relative importance of the standard on the left, compared with the criterion at the top.

	Efficiency 20%	Safety 15%	Costs 25%	Environment 10%	Social Problems 30%
Efficiency 20%		1.3	0.8	2	0.6
Safety 15%	0.75		0.6	1.5	0.5
Costs 25%	1.25	1.6		2.5	0.82
Environment 10%	0.5	0.6	0.4		0.33
Social Problems 30%	1.5	2	1.2	3	

For example, energy efficiency is 1.3 times more important than safety, but 0.8 as important as costs.

Following the same structure for the multi-criteria analysis the results are the following.

Table 15: Results from the second MCDA for every H2 generation process.

	Percentage	Grey	Blue	Turquoise	Green
Efficiency	.20	0.8	0.4	0.4	0.6
Safety	.15	0.3	0.3	0.45	0.45
Costs	.25	1.25	1	1	0.5
Environment	.10	0.1	0.3	0.3	0.4
Social Problems	.30	0.3	0.9	0.9	1.2
		2.75	2.9	3.05	**3.15**

The best option is green hydrogen followed by turquoise and then blue hydrogen and the worst technology related to the experts' criteria from the IRENA survey is grey hydrogen.

4.7.3 THIRD EVALUATION (1000minds)

To evaluate the system using the software 1000minds, the ranks along with each criterion had to be defined. Once they were implemented, the program generated hypothetical questions, including two criteria at a time, and it was even possible to add more levels involving up to the number of criteria used in the assessment. (An example of these questions is included in the appendix in Figure 2). Despite that, the accuracy of the program is sufficient with the evaluation of two criteria each time and it gets harder to evaluate with three or more criteria at the same time.

An additional comment on this assessment is that for this technology is a bit tricky to answer the questions because, in the end, we are trying to reach a sustainable goal where within the renewable energy transition there must be a combination of all areas at their highest level. Having said that, future deployment has to provide the best for the safety, environment, energy efficiency, society, and costs. However, if sometimes is a bit complicated to achieve, with the enhancement in current technologies, and raising awareness in our communities, the transition will be facilitated.

For this Paprika technique the steps to take are the same as the point system; 1) define the objective 2) define criteria, 4) list the option, 5) rate the options. The difference with the other analyses is that numbers 3) weight the criteria and 6) calculate the best option, are produced with a mathematical algorithm used by the program generated with hypothetical questions that the evaluator has to answer.

The valuation for each option as a result of the hypothetical questions got the following values:

Efficiency: 28.6 %
Safety: 20.4
Costs: 20.4%
Environmentally friendly 16.3 %
Social problems: 14.3 %

The main points that were considered here are:

If the questions included a combination of any criteria valued at their worst level, the question was skipped and not taken into consideration. For instance;

Which of these hypothetical options do you prefer?

1) Environmentally friendly *Very low & Social problems *Medium (or)
2) Environmentally friendly *Very high & Social Problems *Very high

In case of two possible questions involved a group with both criteria at their medium level compared to the mix of options with one criterion at its lowest rank, the medium level was selected. A case in point is;

Which of these hypothetical options do you prefer?

1) Safety *Very low & Costs *Very cheap

2) Safety *Medium & Costs *Normal

When the questions involved a good level compared to a medium level from another criterion, the main predisposition was to consider energy efficiency and safety first over the other terms, assuming that ramping up energy efficiency is greatly significant for the smooth transition of renewable energies nowadays, and while safeguarding the safety of their processes, they are also protecting the environment. Whatever affects the ecosystems also impacts human lives to a certain degree. Costs were also considered as important as social impacts. However, the mathematical statistics from the algorithm surprisingly after responding to 18 questions and with a fair accuracy level got the following results:

Table 16: Average score for each hydrogen production technique from the Multi-criteria evaluation taken by the software 1000minds.

Hydrogen production technique	Rank	Score	
Green hydrogen	1st	66.3%	BEST
Turquoise hydrogen	2nd	62.2%	
Grey hydrogen	3rd=	57.1%	
Blue hydrogen	3rd=	57.1%	

The best option similar to the previous evaluations is the green hydrogen technique, followed by turquoise, and then, unexpectedly, an astonishing result that grey hydrogen had the same value as blue. This same percentage was due to the fact that efficiency was graded with the highest value and the costs also added a slight difference.

Software 1000minds showed a graph with marginal effects by applying a mathematical technique called Bezier spline interpolation which helps to smooth the curve through the weights. The function of that curvature enlightens the minor impacts of moving to more elevated levels on every criterion: steady as opposed to expanding as opposed to diminishing negligible impacts. (See graph 1 in Appendix).

4.8 FEW STRATEGIES

The strategies to tackle the possible consequences of an economic decline and catastrophic scenarios were suggested from the social point of view and political and environmental perspectives.

Hydrogen plays a vital role within the energy transition landscape and its deployment should have an integrative approach, and it is indispensable to consider the interaction of many actors such as governments from different countries, citizens, companies, and non-profit organisations. Every country has to evaluate its own resources and measures to incorporate smoothly into the transition market. In the creation of the new infrastructure, such pipelines should be suitable and safe enough to comply with the regulations to transport hydrogen and methane. Environmental impact assessments and risk assessments must be carried out thoroughly at every site.

It is always well known that prevention is better than remediation, so, in the event of these scenarios, the most important is to have a backup plan to dodge, as much as possible, the side effects of one of these potential scenarios. Raise awareness in the communities, and mutual collaboration is necessary to avoid misunderstandings among actors involved and the implications of such technology on the surroundings.

The absence of financial feasibility of creating and utilising hydrogen in the case of an economic decline implies that extra incentives are required, and the ongoing system conditions should be adjusted. There should be initiatives for new investors into European schemes to ensure a productive environment and security. Our society is susceptible to extrinsic situations that we can not fully control, such as atmospheric conditions, cataclysms, or conflicts among politicians that could turn detrimental for people who, without being responsible, suffer the consequences.

Some impact evaluations have to be included before building out the infrastructure to mitigate leakages during hydrogen production, not only to prevent spills into the environment, but also for new regulations from policymakers on where and how to deploy them effectively. Experts must have mutual support to reduce risks and create more accurate measures.

Investigate the possibility of shifting the production of high-consuming energy procedures using hydrogen and renewable energy sources to those with less energy demand to improve energy security and lessen the impact on the environment.

It is essential to consider the e-fuels in the vast majority of sectors and industries. Although the cost is high right now, there is a huge opportunity for cost reduction that can help develop economical solutions to decarbonise sectors with few or no alternatives. Sustainable fuel sources, such as biomass combustion or direct CO_2 capture from the air, are primordial.

5 Discussions

At the moment, many processes are attracting popularity and scientists' attention to discover the economic feasibility and environmental impacts of these new technologies. A great variety of studies show that new technologies for green hydrogen generation with the enhancement of efficiency and scaling up production will reduce the costs of blue hydrogen in the near future.

The levelised cost gap between blue and grey hydrogen is not significant, according to Nikolaidi and Poullikkas. They showed it to be 2.27 USD per kg with sequestration in comparison to that without carbon capture at 2.08 USD per kg (Nikolaidis & Poullikkas, 2017). In addition, the implementation of carbon capture storage drastically dwindles air pollution.

The reason for using simultaneously two scientific methodologies was to increase the reliability and precision of the paper. By applying MCDA, we discovered the main differences from every colour hydrogen technique while applying accurate data and information from current technologies for each of them. With SAFS, we can figure out the predictions and assumptions of the experts on this general topic of hydrogen, depending on the scenarios.

There were also some limitations, as constant during predictive scenarios. We found a minority of articles that were related to social perspectives on hydrogen technologies. A couple of papers we found on the internet talked more about how society is informed by the whole integration of hydrogen and how they feel about that. Another impediment was the relation among certain contextual factors with the scenarios and their impacts on the environment or society. For instance, in case of external events, there were few papers describing particular assumptions that could affect people or nature. Then the assumptions had to be made from our perspective by analysing the information derived from the scenarios and then trying to evaluate them from a sustainability point of view.

The MCDA analysis was more complex using the PAPRIKA technique, owing to a few questions comparing two criteria at their lowest or highest values. The ideal mindset would be to have at least similar values for all of them, but never allow one criterion to be exacerbated to its lowest level.

This paper encourages and delivers information to students, policymakers, and people, in general, to get informed about hydrogen. It also gives insights of the main differences and impacts of the different colours of hydrogen and main methodologies.

Further research on potential pathways that allow the complete set of hydrogen in the energy sector is needed, including the analysis of the fluctuations in GHG emanations to comprehend the contrasts in gas emissions from natural gas based on hydrogen choices. Production sites still require reliable measures to ensure public safety and tackle environmental issues at low costs, especially controls to reduce gas emissions and leakages. The eventual fate of blue hydrogen in a sustainable world relies emphatically upon the degree to which leftover emanations can be eliminated from the production system or compensated through carbon dioxide sequestration as well as on the accessibility of geographical CO_2 stockpiling locations.

Speaking of the improvement in the efficiency of new technologies, a study was done in collaboration with the Fraunhofer Institute from Germany, Copernicus Institute from The Netherlands, and The Higher School of Economics in Russia, where they evaluated four energy demand scenarios depending on the energy gained from potential savings, more efficient technologies and the impact of social trends. They evaluated four energy demand scenarios depending on the energy gained from potential savings, more efficient technologies and the impact of social trends. The results illustrated that social trends have an impact on future energy demand beyond technological and economic efforts (Brugger, Eichhammer, Mikova, & Dönitz, 2021).

The results also demonstrated that the final energy demand could possibly be diminished by 51 per cent through technological improvements in 2050. The domestic sector could contribute with 22%, the industry with 7%, and the specialised upgrades in the transportation area about 14% of the total energy that could be saved. From the consumption saving potential, the energy demand can drop by 20 per cent (Brugger, Eichhammer, Mikova, & Dönitz, 2021).

Although the implementation of hydrogen as a novel technology sounds promising, the reality is that by relating the benefits and impacts from every perspective, and comparing it to the numbers from European Union commissioners, it could be just partially possible. To be fully implemented by 2030 there are a plethora of factors that have to be considered to reach the goal of implementing 10 Mt of green hydrogen and to installing at least 40 GW of renewable hydrogen electrolysers (Furfari, 2021).

There are still many issues to address before fully implementing this technology in the grid system and coupling it with renewable energies. Storage batteries and fuel cell improvements are indispensable and more agreements and covenants among countries to facilitate the exchange of this energy carrier and the new infrastructure to trade hydrogen. However, the ideal situation would be to get hydrogen stored in better conditions to use it during high energy demand. The use of pipes during the initial phases of operation is one of the major challenges and the supply and demand must be coordinated to ensure their correct use.

Hydrogen could become a valuable part of the energy transition for a few reasons; firstly, it is a solution to tackle the fluctuations associated with wind and solar energy. When weather conditions hamper the ability to harness renewable energies, the energy stored in the form of hydrogen is meaningful to continue with the supply of electricity. Secondly, the steel industry could use electrolysis using green hydrogen from solar panels or wind plants to produce steel using gaseous hydrogen instead of metallurgical coal (coke). Thirdly, as a means of transportation, it would be ideal for long routes because shipping energy

over significant distances is typically simpler as atoms in their liquid or gaseous forms, and fuels have higher energy densities than electricity. The majority of natural gas is transported throughout the world by large-scale pipelines or boats, thus, similar techniques might be used for hydrogen.

It can also be converted to ammonia, methanol, or any other organic fuel, but this would include some losses during its liquefaction; therefore, the best idea would be to produce hydrogen on-site. To ensure continuous worldwide hydrogen trade, a greater range of storage activities will be needed and hydrogen storage at terminals is probably required as a backup plan in case of supply outages.

Some countries are geographically better located than others across the globe, and by virtue of that, hydrogen technology could be swiftly assembled in the energy transition and prove those regions with more advantages in harnessing renewable resources.

6 Conclusions

This review illustrated some insights into the sustainability analysis of various hydrogen production systems. Hydrogen production technologies were also reviewed, such as steam methane reforming, methane gasification, coal gasification, pyrolysis, electrolysis, and their main differences. In addition, a Sustainability Assessment Framework was formulated to provide some straightforward ideas to bear in mind in case of an economic decline, technological improvements, and external events. The paper also presented summarised but comprehensive details of these technologies based on costs, environment, society, efficiencies, and safety, which were evaluated with a multi-criteria analysis. The second part of this work presented a multi-criteria decision analysis that contributed to evaluating the main criteria from a sustainable perspective on all these hydrogen production techniques.

According to the evaluation in this paper, green hydrogen is the best option to yield energy from hydrogen, followed by turquoise and ensued closely by blue. Finally, the least favourable is grey hydrogen. Of the three evaluations, the first two showed that green and turquoise hydrogen are the leaders from a sustainability view and the least favourable is grey hydrogen.

Grey hydrogen is produced with fossil fuels as was previously mentioned therein, it has the cheapest technology at present, but it is also the most polluting with the highest amount of greenhouse gas emissions to the atmosphere. Blue hydrogen is a better option to reduce carbon dioxide emissions, but when applying Carbon Capture Storage mechanisms, the energy is diminished with some losses during the process and hence the costs increase. Turquoise hydrogen is a new mechanism that is being explored on a great scale, but it gives the benefits that it is almost zero carbon source and the products can be used and sold in the industry. And last but not least, Green hydrogen is the best production method theoretically speaking without gas emissions and coming from natural resources, with the only disadvantage of high costs for its implementation, and the flexibility options that have to be solved in a scenario with a great number of renewable energies where the demand of electricity is higher than the supply during unfavourable conditions of climatic circumstances or geographical position where the wind or sunlight can not be harnessed completely.

Due to the nature of new technologies in the vision of future energy systems, statements about future scenarios are highly uncertain and sometimes difficult to predict. Preparations for hydrogen implementation should not only be based on environmental impacts, but a set of socio-economic indicators, such as political stability, unemployment, energy demand, electrification status, the participation of civil society, economic, development objectives, and capital requirements for storage or infrastructure.

Hydrogen innovations currently still have various difficulties which require participation among specialists and industries to enhance the hydrogen market by utilising the new and innovative created technologies. The design of the regulatory experiments is an important and useful tool to foster sustainable development and to analyse the scenarios with empirical evidence, which in turn, will provide insights and benefits to politicians, individuals, and industry actors.

Revising new cutting-edge technologies is paramount to avoid negative impacts that could occur during their life cycle. The benefits of novel devices are usually shown in research papers but it should not be forgotten the evaluation of possible circumstances in the medium and long run and always remember the primary meaning of sustainability of the United Nations.

The more technological assessments are portrayed, the more knowledge is gained about the state-of-the-art innovations, and it is easier to encounter problematic failures or occurrences in their deployment and avoid them in the following invention.

In the face of forces that are beyond our comprehension and more powerful than us, unconsciously, it is assumed that by making better predictions, the world may be more successfully prepared to avoid possible consequences or calamities, and know how to properly act upon those scenarios leading us to a better future.

Policymakers are capable of choosing more wisely with additional knowledge with the enhancement of technological development. However, just as in earlier eras, the hunger for information along with good values and principles are required to achieve a more sustainable and cleaner planet. More assessments are necessary alongside collaborations among sectors, including and fostering the citizen's welfare and the environment's protection.

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8 Appendix.

8.1 Appendix – Acronyms

Table 17:Acronyms used in the paper.

ACRONYMS	**MEANING**
MCDA	Multi Criteria Decision Analysis
SAFS	Sustainability Assessment Framework for Scenarios
SMR	Steam Methane Reforming
CCS	Carbon Capture Storage
PEM	Proton Exchange Membrane
ATR	Auto Thermal Reforming
AE	Alkaline Electrolysis
PEC	Photo Electrochemical Cells
LCOH	Levelised Cost of Hydrogen
SOEC	Solid Oxide Electrolysis cells
IEA	International Energy Agency
IRENA	International Renewable Energy Agency

8.2 Appendix – Energy efficiency values from literature

Table 18: Values from literature for Grey Hydrogen for the energy efficiency rating.

	Grey Hydrogen		
Technology	**Value 1**	**Value 2**	**Bibliography**
Steam Methane Reforming	70	85	ElShafie,2019
Partial oxidation	60	75	Pinsky, 2020
Coal gasification	60	-	ElShafie,2019
Autothermal Reforming	60	75	ElShafie, 2019
Average	62.5	78.33	
General Average	**69**		

Table 19: Values from literature for Blue Hydrogen for the energy efficiency rating.

Blue Hydrogen			
Technology	**Value 1**	**Value 2**	**Bibliography**
Steam Methane Reforming with CCS	68	69	Osman_2021 & IEA_2019
Partial oxidation with CCS	45	-	Assumptions
Coal gasification with CCS	58	-	IEA,2019
Autothermal Reforming with CCS	45	-	Assumptions
Average	54	69	
General Average	**57**		

Table 20: Values from literature for Turquoise Hydrogen for the energy efficiency rating

Turquoise Hydrogen			
Technology	**Value 1**	**Value 2**	**Bibliography**
Pyrolisis	35	50	Kumar,2019 & Nikolaidis,2017
Methane Pyrolysys	58	58	SanchezBastardo,2021
Plasma Reforming (Methanol)	34	62.4	ZHANG,2017
Plasma Reforming (Ethanol)	9	85	ElShafie,2019
Average	34	63.85	
General Average	**49**		

Table 21: Values from literature for Green Hydrogen for the energy efficiency rating.

Green Hydrogen			
Technology	**Value 1**	**Value 2**	**Bibliography**
Alkaline electrolyser	50	78	IRENA,2020
PEM electrolyser	47	85	IRENA,2020
Solid oxide electrolysis cells	45	55	IRENA,2020
Anion Exchange Membrane	57	69	IRENA,2020
Average	49.75	71.75	
General Average	**61**		

Table 22: Costs from five sources for blue, turquoise, grey and green hydrogen. Values on the parentheses are the average from the digits on the left. Values are expressed in dollars per 1 kilogram of hydrogen generated.

Bibliography	Grey Hydrogen	Blue Hydrogen	Turquoise Hydrogen	Green Hydrogen
(IEA, 2021)	0.5 - 1.7 (1.1)	1.2	----	3 – 8 (5.5)
(Global CCS Institute, 2021)	----	2	----	2.30 - 7.70 (5)
Atom scientist (Bulletin of the Atomic Scientists, 2021)	----	2-3 (2.5)	2	5 -7 (6)
(Nikolaidis & Poullikkas, 2017)	----	----	1.34–2.27 (1.8)	----

(Energy Transitions Commissions, 2021)	0.7 - 2.2 (1.45)	1.3 - 2.9 (2.1)	1 - 2.5 (1.75)	2.6 - 4.5 (3.5)
Average	**1.27**	**1.95**	**1.77**	**5**

8.3 Appendix – Software 1000 minds

Figure 2: Example of the questions from the software 1000minds

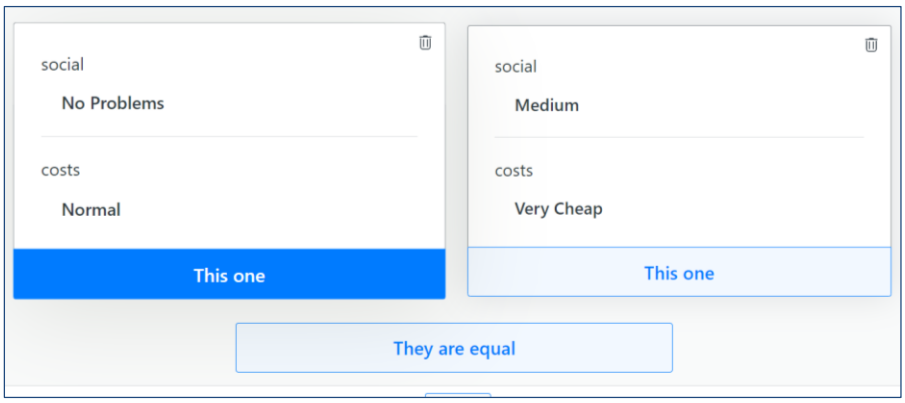
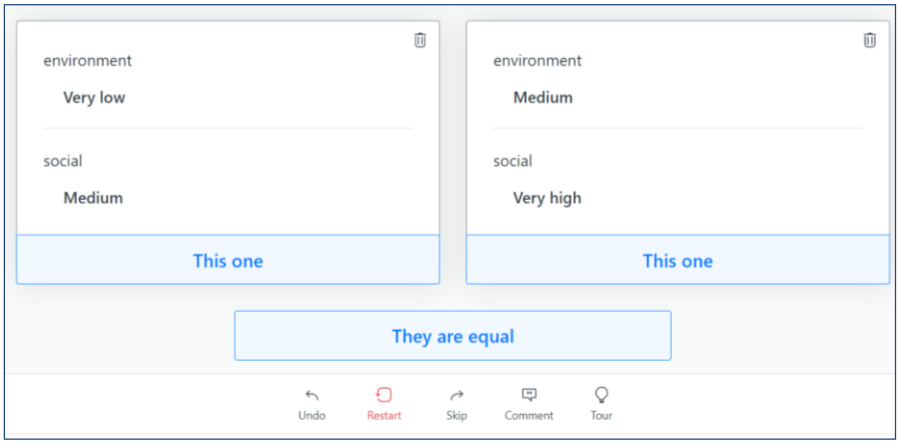
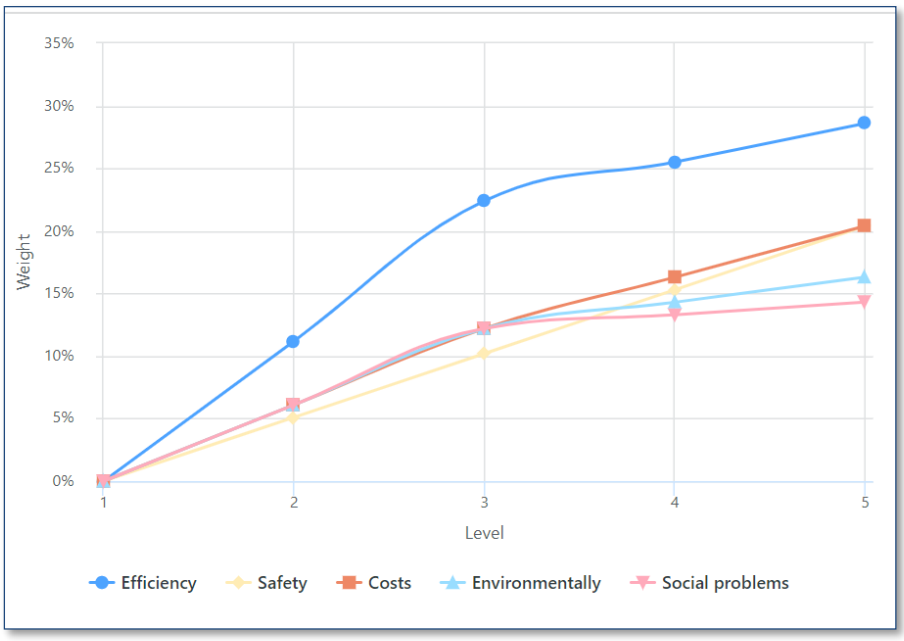


Figure 3: Example of the questions that were skipped



Graph 1: Marginal effects: Each criterion's value illustrates the shape of the weights for the levels on the criterion. (Taken from the software 1000minds)



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.....

(Future scenarios in the near future: sociological, environmental, economic, and energetic aspects)
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