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Review

Analysis of the European Strategy for Hydrogen: A Comprehensive Review

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Abstract: This review focuses on analysing the strategy and aspirations of the European Union within the hydrogen sector. This aim is achieved through the examination of the European Parliament's hydrogen strategy, allowing for a study of actions and projects in hydrogen technologies. The Parliament's hydrogen strategy is the document that provides the guideline of how the EU intends to function in the hydrogen sector and manages to cover a wide range of topics, all of them significant to represent the entirety of the hydrogen sector. It touches on subjects such as hydrogen demand, infrastructure, research, and standards, among others. The review discusses also the aspect that the EU intends to be a leader in the hydrogen sector, including the large-scale industrialization of key elements such as electrolysers, and this purpose is corroborated by the large number of associations, strategies, plans, and projects that are being established and developed by the European Union. The most important conclusions to learn from this analysis are that hydrogen has many of the right characteristics to make it the key to decarbonisation, especially in hard-to-abate sectors, and that it is bound to be one of the main actors in the imminent green transition. Moreover, hydrogen seems to be having its breakthrough, and this field's development can have benefits not only from an environmental perspective but also from an economical one, enabling the way into the green transition and the fight against climate change.

Keywords: hydrogen energy; hydrogen economy; energy system; European Commission

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1. Introduction

The main objective of this review is the analysis of the European Union's view and strategy for hydrogen, which is crucial to attain an understanding of the hydrogen sector and comprehend its evolution within the green transition. The reason for this is that the EU is a very important actor in the sector, so the measures it takes and the projects it develops have a major influence on the hydrogen market's advancement. Hydrogen is an energy vector currently being targeted to play a fundamental role for the energy transition towards a net-zero emissions energy system [1,2]. A hydrogen economy would require efficient and green production of hydrogen [3,4], large-scale storage and distribution of hydrogen [5,6], and final end-use of hydrogen covering major applications such as industry, transport, residential, and renewable feedstock [7].

Nevertheless, as was said, the principal goal is to study the approach of the European Union to the hydrogen sector, which is accomplished using the European Parliament's hydrogen strategy [8] as the channel and checking how its goals are being developed currently.

This review is developed within an energy context that strongly influences its content. While the main subject of this review is hydrogen, including its applications and the strategies elaborated, it is essential to consider the circumstances in order to understand hydrogen's role.

Probably the first concept to arise when thinking about energy context is climate change and the fight against it through decarbonisation and initiatives such as the Paris

Agreement [9]. This agreement joined nations worldwide in 2015 to undertake the task of combating climate change, aiming to maintain the rise in global temperature in this century below 2 °C above pre-industrial levels and even limit it to 1.5 °C. Moreover, there are additional objectives within this agreement, such as encouraging the participants to maintain their GHGs sinks (forests, for instance) or enhancing climate change education and training, public participation, awareness, and access to information.

One way to assess the energy context is through energy-related information and, particularly, the data presented by the International Energy Agency (IEA), although it has to be stated that the data are only collected until 2019, so they do not reflect the current post-pandemic situation. It is also important to note that the IEA data regarding the European Union include the United Kingdom (EU-28) since the figures provide information up to 2019, before the UK withdrew from the EU.

In Figure 1, it is seen that the energy consumption worldwide follows an increasing trend, covering renewable sources but also those that are fossil-based, while the EU has been able to stabilise and even begin a decreasing trend in consumption in recent years.

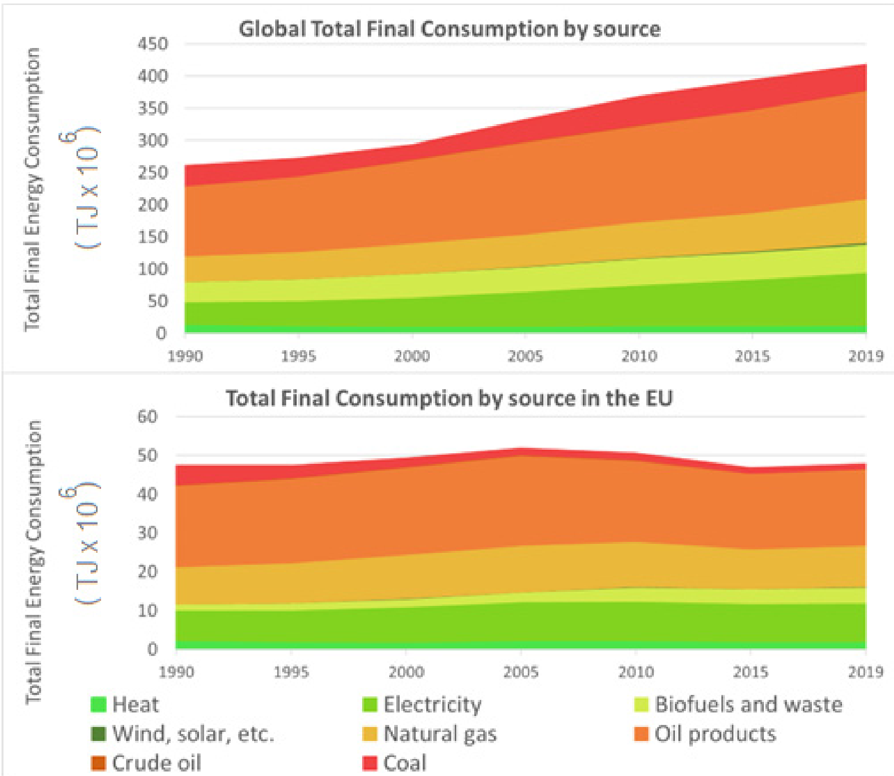

Figure 1. Comparison of the total final consumption by source worldwide and in the EU [10,11].

Actually, the final energy consumption in the EU dropped around 8% from 2019 to 2020, reflecting the effects of COVID-19 on consumption habits and industrial and public activity, such as the decrease in transport and industry consumption due to lockdowns and restrictions, but this is clearly an out of the ordinary situation that does not really reflect the trend.

In Figure 2, the comparison is similar to the previous one: the global CO_2 emissions are increasing but the trend in the EU is decreasing. In the past few years, the EU has managed to remarkably reduce its CO_2 emissions in the electricity and heat production and industry sectors and, in most sectors, in a more or less significant manner.

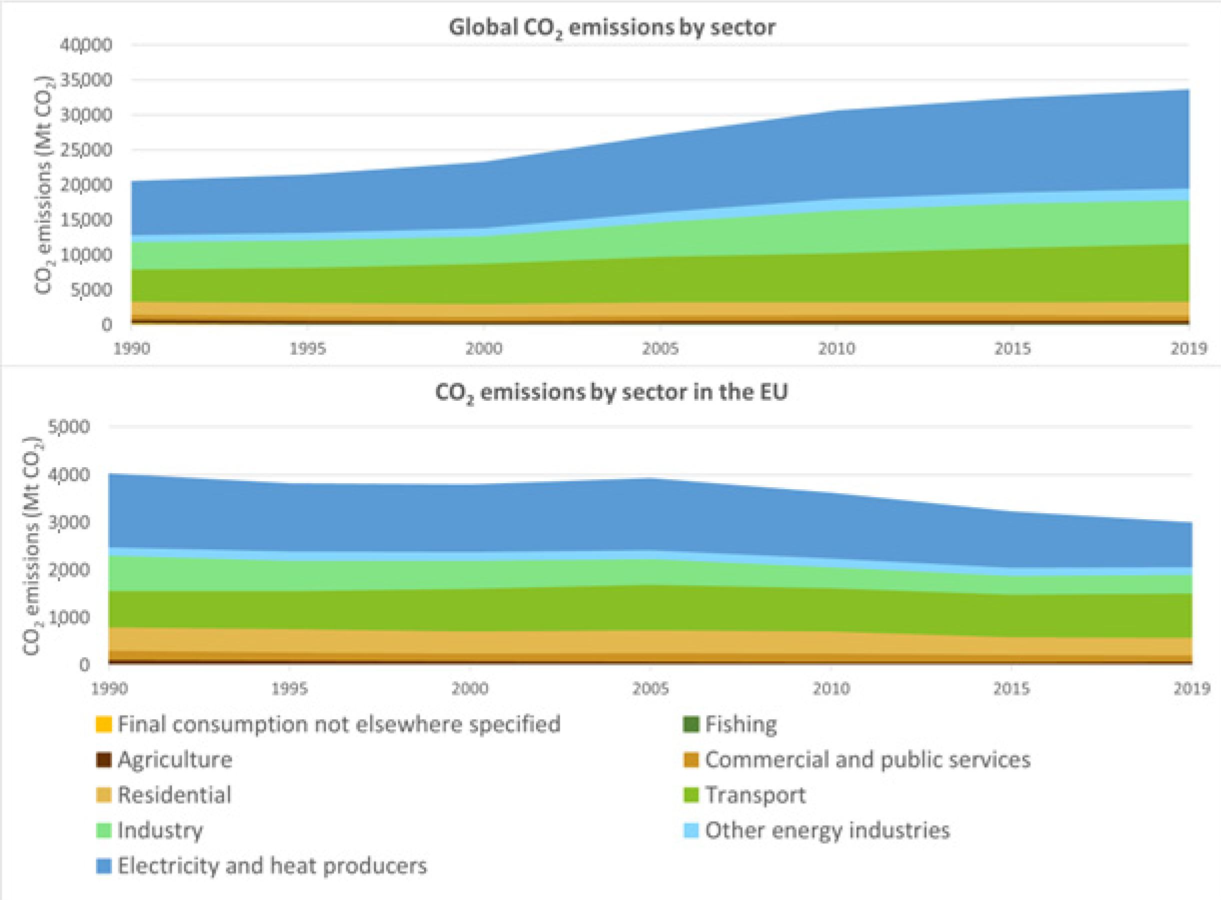

Figure 2. Comparison of CO_2 emissions by sector globally and in the EU [12,13].

However, the one sector that goes against the trend is transport, which is not surprising given that it is one of the hard-to-abate sectors. This will be tackled later in the review since hydrogen technologies will be an important part of the decarbonisation of the sector.

One reflection that can be obtained is that energy demand and, therefore, consumption is increasing and will continue to do so in a context in which population (even though growth rate is around 1%) is set to increase by 2 billion people by 2050, reaching almost 10 billion inhabitants. There will be an even larger demand for resources, and energy is no exception.

It is also interesting to see the difference between the EU and the global trends. The European Union's position can be associated with the fact that it already is a developed economy that can focus on environmental matters more than developing economies or economies in transition.

The EU is, therefore, in a green transition, focusing on reducing energy demand and increasing energy efficiency and decarbonisation. This transition, however, needs to be safe and accessible for the population, but the market is susceptible to political and economic instability and phenomena such as the COVID-19 pandemic.

Actually, the global and especially the EU energy markets are currently facing the impact of Ukraine's invasion executed by Russia in the beginning of the year 2022. This is evidently a huge humanitarian crisis and can be looked at from many angles, but in terms of this review, it is appropriate to focus on its impact on the energy markets.

Russia is one of the leading producers of both crude oil and natural gas and is, indeed, the world's top natural gas exporter, with the EU being highly dependent on this trade. In 2020, the EU imported 29% of its extra-EU crude oil, 43% of its natural gas, and 54% of its solid fossil fuel (coal) from Russia.

The COVID-19 pandemic had already contributed to the increase in energy prices, with natural gas prices reaching 180 €/MWh in December 2021, and this conflict has made things worse.

The sanctions imposed on Russia and the supply interruptions have led to a severe increase in prices and lack of security of supply. The European Commission is already taking action, having proposed a plan to overcome the dependency from Russia's fossil fuels before 2030, tackling the high natural gas prices and their effect on electricity prices and gas storage.

One final takeaway could be that the green transition and the quest for climate neutrality are the only way to at least mitigate the effects of climate change and global warming. Furthermore, they can also be an opportunity for the development and deployment of new low-carbon or decarbonised energy solutions that can be competitive while better for the environment, and it is important to recognise how these technologies and ambitions can constitute the energy context of the future and how hydrogen has a crucial role to play.

Hydrogen, and particularly green hydrogen, is a key potential alternative for decarbonisation and the phasing out of fossil fuels and also for energy system integration. It also presents itself as a buffer for renewable energy production thanks to its storage aspect, and this aspect can also contribute to security of supply and independency. It also represents an option to reduce CO_2 emissions in sectors difficult to decarbonise.

Its contribution to the sustainability of the EU's energy system is not the only perspective to be taken into account, since procuring a competitive hydrogen economy represents an economical opportunity. According to the European Parliament, the H_2 economy could entail the creation of up to a million direct jobs by 2030 and 5.4 million by 2050.

2. European Organisations, Initiatives, and Plans regarding Renewable Energy and Hydrogen

It is appropriate to first explain some of the initiatives and plans that are crucial to the hydrogen development topic and mentioned throughout the hydrogen strategy. Those are:

- Paris Agreement [9]: This agreement was already mentioned in the Introduction section, which is not rare given that it is one of the most popular environmental initiatives worldwide. As said before, through this initiative, different nations aim to maintain the rise in global temperature in this century below 2 °C above pre-industrial levels or even limit it to 1.5 °C.

Some of the crucial aspects of this pact to fight climate change, in addition to the temperature goals and in addition to those mentioned in the introduction, are the achievement of the global peaking of GHG emissions, the establishment of "nationally determined contributions" by each country, as well as National Adaptation Plans, and even the ability to cope with the unavoidable negative consequences of climate change.

- EU Green Deal [14,15]: This European environmental strategy is the main approach of the European Union to tackle climate change and its effects. The actions within the Green Deal cover fields such as energy, industry, climate, environment, transport, etc.

The European Union member states have committed, among other things, to reduce GHG emissions by 2030 by 55% compared to the GHG emissions in 1990. In addition to the emissions reduction, the Green Deal aims to transform and bring innovation to the European economy through the creation of jobs or the decrease in energy dependency from other countries.

Within the Green Deal, many laws and strategies have been adopted, such as the European Climate Law, the EU Industrial Strategy, the EU Strategy for Energy System Integration and the European Strategy for Hydrogen, and the REPowerEU plan.

- REPOWEREU [16,17]: The REPowerEU Plan was recently issued by the European Commission as a consequence of the effects of the Russian invasion of Ukraine on the energy market, focusing mainly on achieving energy independency, so as to not be subjected to Russian fossil fuels.

Therefore, the plan includes measures that will accelerate the green transition, centred on the production of renewable energy in the EU (reduces both emissions and dependency), the saving of energy (through efficiency measures, for instance), and the diversification of the EU's energy supply.

- UN Sustainable Development Goals [18]: The United Nations developed the 17 sustainable development goals as part of its 2030 Agenda for Sustainable Development; all the UN member states committed to these goals in 2015, and every year, the UN reports the progress achieved. While all of these goals are equally important and crucial to sustainable growth, the ones concerning the topics of this review are: "Goal 7: Affordable and clean energy", "Goal 9: Industry, innovation and infrastructure", and "Goal 13: Climate action".

These goals have targets and indicators associated with them.

The first one focuses on enabling access to sustainable and affordable energy for everyone, and, for example, one target is to increase the share of renewable sources in the energy mix by 2030 and the indicator associated is that share.

The second goal mentioned aims to promote sustainability for industrialisation and innovation, as well as the creation of infrastructure. An example of the target is the aim to improve research and promote growth in the number of researchers, which is why one of its indicators is the number of researchers per million inhabitants.

Finally, goal 13 takes on climate change and the fight against it, one of its targets being that member states include measures to fight climate change in their national plans and its indicator being total GHG emissions per year.

Nevertheless, it is important to reiterate that all 17 goals are significant, and some cover broader aspects that have an effect on the energy sector and, therefore, the role of hydrogen.

That being explained, it is appropriate to take a look at some of the organisations and plans that appear during the entirety of this review: those that are mentioned in the European Parliament's hydrogen strategy and also those that come up in the elaboration of its analysis; therefore, by no means is this an exhaustive list of the bodies and strategies associated with the hydrogen sector but a gathering of some that have come up during the study.

The list can be seen in Figure 3, although there are more organisations, strategies, etc., appearing throughout the document. Out of the 36 listed, 28 are European, which can mean that they were either founded, funded, or appointed by the European Commission or by European companies. The other 8 are international and include the EU. Again, it is not representative of the entire sector, but it is predictable that in an analysis of the EU hydrogen strategy, the majority of bodies and plans referred to are European.

It is also remarkable to note that most of the hydrogen associations and plans were created in these past years, and even some of those concerning renewable energy and sustainability. This shows how hydrogen is actually having what is hopefully its definitive breakthrough and how its role in decarbonisation is backed up by organisations, plans, projects, etc.

	Decarbonisation, renewable energy, sustainability	Hydrogen
Organisations Partnerships Coalitions…	• Clean Aviation Joint Undertaking • European Union Agency for the Cooperation of Energy Regulation (ACER) • European Partnership for transforming Europe's rail system • EU Clean Steel Partnership (CSP) • European Association for Storage of Energy • European Partnership – Towards zero-emission road transport (2ZERO) • European Partnership for Clean Energy Transition • Processes4Planet • International Energy Agency (IEA) • International Renewable Energy Agency (IRENA) • Carbon Neutrality Coalition • Clean Air Task Force	• Fuel Cells and Hydrogen Joint Undertaking • Clean Hydrogen Partnership • Hydrogen Europe • European Clean Hydrogen Alliance • Renewable Hydrogen Coalition • H2 Island Hub • International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) • European Green Hydrogen Acceleration Centre • HySafe
Plans Strategies…	• Carbon Contracts for Difference • The action plan for critical raw materials • EU Strategy for Energy System Integration • Sustainable and Smart Mobility Strategy	• European Parliament's "A European Strategy for Hydrogen" • European Commission's "A Hydrogen Strategy for a climate-neutral Europe" • European Hydrogen Backbone Initiative • Clean Energy Ministerial Hydrogen Initiative
Platforms projects…	• The Important Projects of Common European Interest (IPCEIs) • EUREKA • Clean Energy for EU Islands	• Mission Innovation Hydrogen Valley Platform • Hydrogen Public Funding Compass • CertifHy™ • HyResponder

Figure 3. Organisations, initiatives, plans, and platforms regarding renewable energy and sustainability as well as hydrogen.

3. The European Strategy for Hydrogen

This section can be considered the core of the study since it consists of the review of the document generated by the European Parliament, "A European Strategy for Hydrogen", expressing its goals and wills on this topic.

The European Parliament resolution of 19 May 2021 on a European Strategy for Hydrogen [1] comprises three sections:

- Documents, reports, communications, directives, and just about everything falling under the spectrum of information the European Parliament has regarded in order to create this text.
- Goals and starting point for the hydrogen strategy.
- The statements made by the European Parliament.
- Moreover, the statements are also subdivided, facilitating the review and analysis. These subdivisions, which are subsequently developed, are the following:
- Overall.
- Hydrogen classification and standards.
- Ramping up hydrogen production.
- Citizen engagement.
- Hydrogen infrastructure.
- Hydrogen demand.
- Research, development, innovation, and financing.
- International cooperation on hydrogen.
- The role of hydrogen in an integrated energy system.

Nevertheless, before commencing the thorough analysis of these sections, it is appropriate to go into detail about the bodies associated with this document.

In the first place, there is the European Parliament, the organisation behind the document being studied. This legislative body is one of the three established in the European Union and, along with the Council of the European Union, has the role of the legislator/has the task to adopt EU legislation determined by budget matters. This Strasbourg-based organisation comprises 705 Members of the European Parliament (MEPs) who are voted into power and are organised in political groups and is presided over by Roberta Metsola.

Finally, it is pertinent to note that the European Parliament supervises the work of different EU bodies, including the European Commission.

Second, the member states can be found mentioned all throughout the document.

Finally, across this European strategy for hydrogen, the European Commission is repeatedly alluded to, being urged, called on, encouraged, asked, or requested to accomplish or execute something, among others, by the Parliament.

The European Commission is the branch of the European Union that enforces the law, the executive body. It consists of an organisation headed by a President and 27 members of the Commission or "Commissioners" or "the College of Commissioners" headquartered in Brussels and currently presided over by Ursula von der Leyen.

The Commission is divided into directorates-general according to the various policy areas (budget, climate action, defence industry and space, energy, etc),as well as service departments and executive agencies to handle specific issues or programmes.

Regarding the Commission's work, several roles and functions can be found, some of them being: to develop and implement the European Union policies, to participate in the elaboration of the EU's overall strategy, to propose and ensure the correct implementation of EU laws, to plan the European development policy and deliver aid worldwide, and to propose and implement the European Union budget and manage its funding, among other functions.

3.1. Statements

These statements are expressed by the European Parliament; therefore, this is the body that stresses, welcomes, underlines, etc., all throughout the document, expressing its views on a hydrogen strategy. For the review, per se, different excerpts from the document are quoted literally, which are recognised by the use of italics and analysed by topic.

3.1.1. Overall

In this first section, there are six statements regarding different generic aspects of hydrogen relevant to the strategy.

Some of those are that:

> *The EU hydrogen strategy* [needs to] *cover the whole value chain* [and also has to] *be compatible with* [the agreements, plans, and goals already existing, particularly:] *the Paris Agreement, the EU's climate and energy targets for 2030 and 2050, the circular economy, the action plan for critical raw materials and the UN Sustainable Development Goals*.

The EU Parliament:

> *Welcomes the hydrogen strategy for a climate-neutral Europe proposed by the Commission including the future revision of the Renewable Energy Directive, as well as [...] the Member State strategies and investment plans for hydrogen*. [It] *also urges the Commission to align its approach on hydrogen with the new EU industrial strategy and make it a part of a coherent industrial policy*.

The Commission's hydrogen strategy was actually released together with the European Clean Hydrogen Alliance as part of the New EU Industrial Strategy and, therefore, is in line with it.

The New EU Industrial Strategy [19] was presented by the Commission in March 2020. This policy aimed to support the twin transitions (digital and green), support SMEs, or maintain Europe's competitiveness, among other objectives.

However, as the Commission remarks, shortly after the COVID-19 pandemic was officially declared, the lessons learned from that experience led the Commission to update the industrial strategy in May 2021, keeping the same priorities but also adding some new points:

- Reinforce the resilience of the single market.
- Support EU's open strategic autonomy by addressing strategic dependencies.
- Accelerate the twin transitions.

Another aspect discussed in this section is:

> *The importance of the principle of technology neutrality,* [specifically:] *the EU Parliament underlines the importance of a resilient and climate-neutral energy system based on the principles of energy efficiency, cost efficiency, affordability, and security of supply*. [It also] *notes that direct electrification from renewable sources is more cost-, resource-, and energy-efficient than hydrogen [. . .] but factors such as security of supply, technical feasibility and energy system considerations should be taken into account when determining how a sector should decarbonise*.

One more point discussed in this section is:

> *The need to maintain and further develop EU technological leadership in clean hydrogen through a competitive and sustainable hydrogen economy with an integrated hydrogen market*.

Indeed, the role of the European Union in relation to renewable hydrogen is that of technological leadership, and maintaining that is fundamental to the hydrogen market.

Following this thinking, the Renewable Hydrogen Coalition exists to represent investors, entrepreneurs, companies, industrial off-takers, and more in the field of hydrogen with the view of positioning Europe as the leader in renewable hydrogen technologies.

Moreover, the Commission declared in a press release in May 2022 that the Commissioner for Internal Market and 20 industry CEOs signed a joint declaration within the European Electrolyser Summit committing to a tenfold increase in electrolyser capacity, as detailed in the section, "Ramping up hydrogen production".

In this joint declaration, it is stated that to reach the targets proposed, the EU needs to ramp up its manufacturing capacities for renewable and low-carbon hydrogen production, principally electrolysers, as this technology is regarded as the main backbone for green hydrogen production [20,21].

Currently, the manufacturing capacity of electrolysers in Europe is approximately 1.75 GW of hydrogen output per year, and this number is expected to grow exponentially following the Fitfor55 and RePowerEU targets.

This sector covers a larger spectrum of technologies: electrolysers manufacturers, suppliers of electrolyser components and materials, infrastructure, etc. Therefore, the European Clean Hydrogen Alliance will establish an electrolyser partnership to connect them.

The companies that signed the joint declaration [22] are multinationals, and some are Europe-based such as the Italian De Nora or the French Elogen. These enterprises have committed to work on integrating the hydrogen value chain, to deal with the raw materials dependency, to implement recycling systems, and to invest in research, development and innovation in their fields. They have also committed to be aligned with the EU climate goals and plans, making the reception of state aid or funding easier and faster.

This part mentions the hydrogen valleys too, since the EU Parliament:

> *Recognises the efforts undertaken by hydrogen valleys [. . .] throughout the EU [. . .], underlines their important role initiating the production and application of renewable hy-*

drogen and urges the Commission to build on these initiatives, support their development and help those involved to pool their know-how and investments.

Hydrogen valleys are defined as regional ecosystems that cover the value chain, linking hydrogen production, storage, transportation, and various end uses such as mobility, energy, or industrial feedstocks. They are also known as hydrogen hubs and are usually recipients of multi-million EUR investments. Many projects have emerged worldwide and are intended to impel economic development in the geographic regions they are located in [23].

To determine the characteristics of the valleys, it is fitting to refer to the report issued in the Mission Innovation Hydrogen Valley Platform in March 2021, Hydrogen Valleys, Insight into the emerging hydrogen economies around the world [24].

According to the report, hydrogen valleys have some common traits despite the different types of projects and the various circumstances that determine them. These characteristics are:

- They are large in scale.
- They have a clearly defined geographic scope.
- They cover the value chain broadly.
- They supply to various end sectors.

Being large is something that could be deduced since it was mentioned before that these projects involve multi-million EUR investments. Furthermore, they encompass smaller projects within themselves, constituting the main hydrogen valleys.

They cover a delimited geography, and that is a characteristic present whether the scope is local or international.

The considerable value chain coverage is, again, part of the hydrogen valley definition and so is the wide range of end uses and sectors in which hydrogen is utilised.

One main attraction of the hydrogen valleys is the fact that they are integrated systems; since they cover the value chain, they combine supply and demand. This means they are crucial in the development of the hydrogen industry and economy.

Moreover, while climate change is still the principal motivation behind projects, there are other significant purposes, including economic interest, energy security, or industrial strategy.

However, and this is a topic that is going to appear eventually throughout this review, regulation and policy entail barriers in the hydrogen sector. Some of the hurdles hydrogen valleys can sustain are: difficulty with the authorization of permits for infrastructure or end-use applications, overly strict safety regulation or no regulation at all, or taxes on electricity from RES, among others [24–27].

In addition, in this section, the Parliament expresses the critical role of renewable hydrogen, stating that:

Hydrogen produced from renewable sources is key to the EU's energy transition as only renewable hydrogen can sustainably contribute to achieving climate neutrality in the long term, [but also] *notes with concern that renewable hydrogen is not yet competitive*.

The Commission and the member states are then urged to tackle this lack of competitiveness.

Finally, the Parliament:

Highlights that hydrogen-derived products such as synthetic fuels produced with renewable energy constitute a carbon-neutral alternative to fossil fuels and can [. . .] contribute [. . .] to the decarbonisation of a wide variety of sectors.

3.1.2. Hydrogen Classification and Standards

In this section, many topics are discussed. First, the matter at hand is the classification of hydrogen.

According to the EU Parliament:

A common legal classification of the different types of hydrogen is of utmost importance, [and] *the classification proposed by the Commission [is welcomed] as a first step*. [This classification will require] *comprehensive, precise, science-based and uniform EU-wide terminology* [that will enable the adoption of] *national legal definitions;* [therefore, the Commission is urged to] *conclude its work on establishing such terminology*.

[Furthermore, the classification] *should be determined according to an independent, science-based assessment, stepping away from the commonly used colour-based approach;* [moreover, some desired characteristics for the classification are:]

- It should be based on the life cycle GHG emissions throughout hydrogen's entire production and transport process
- It should take into account transparent and robust sustainability criteria in line with the principles of the circular economy
- It should be based on averages and standard values per category, such as the objectives of sustainable use and the protection of resources, the handling of waste and the increased use of raw and secondary materials, pollution prevention and control, and finally, the protection and restoration of biodiversity and ecosystems.

Regarding these statements, the first question that arises is: What is the classification proposed by the Commission?

The Commission's proposed classification is elaborated according to the carbon content of hydrogen, which varies based on the technology and energy source associated with the hydrogen production. The different types are listed in Figure 4.

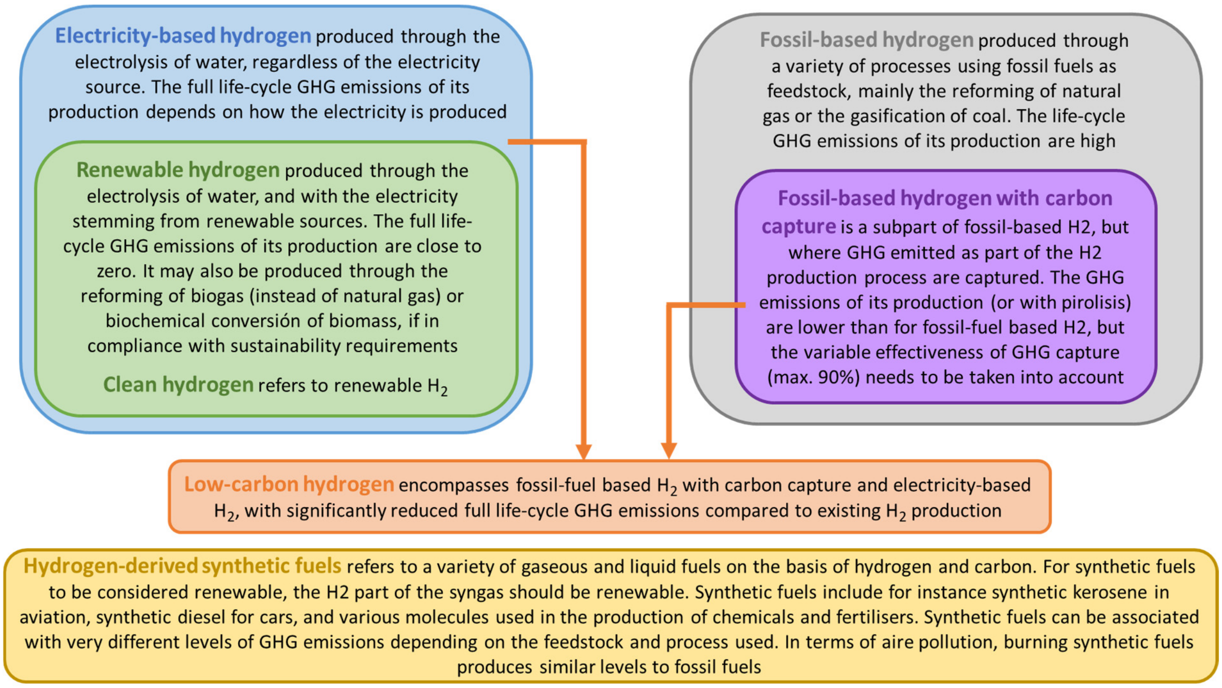

Figure 4. Hydrogen classification proposed by the European Commission [28].

However, the EU Parliament:

Notes [...] that avoiding using two names for the same category of hydrogen, namely 'renewable' and 'clean', as proposed by the Commission, would provide further clarification, and [...] that the term 'renewable hydrogen' is the most objective and science-based option.

As explained in the strategy, this categorisation can be a precedent or a model for future classification, particularly in opposition to colour-based classification.

The colour-based classification is the most frequently used. However, not only does it not comply with the characteristics required by the Parliament, it also bears the burden of a lack of homogeneity outside of the main three colours.

The principal hydrogen types within this classification are:

- Green Hydrogen: produced through the electrolysis of water; the electricity that powers the electrolyser comes from renewable sources (wind, solar …); therefore, green hydrogen has no associated GHG emissions. It can also include hydrogen produced from waste biomass.
- Blue Hydrogen: it is produced by steam reforming together with carbon capture and storage (CCS).
- Grey Hydrogen: it is produced from fossil fuels, mostly by steam methane reforming but without carbon capture and storage. Some sources include black and brown hydrogen in this category.
- Brown and black Hydrogen: these types of hydrogen are produced through the gasification of brown coal (brown hydrogen) and black coal (black hydrogen), although some sources consider that hydrogen produced through the gasification of any fossil fuel is black or brown hydrogen. Since there is no carbon capture associated, this is the most environmentally damaging type of hydrogen.
- Turquoise hydrogen: this is the hydrogen produced through methane pyrolysis, resulting in hydrogen and solid carbon. There are no GHG emissions associated with the production itself. However, depending on the source making the classification, there are emissions associated with the mining and transport of the natural gas, emissions associated with how the thermal process is powered, and emissions associated with the use of the solid carbon generated as a by-product (whether it is used or stored).
- Pink/purple hydrogen: hydrogen produced through electrolysis powered by nuclear energy. Sometimes this type is also called red or even yellow, depending on the source making the classification.
- Yellow hydrogen: this colour for hydrogen demonstrates the lack of homogeneity previously acknowledged, since it is used to describe hydrogen produced by electrolysis using electricity from the grid, hydrogen produced by electrolysis using solar power, hydrogen produced through direct water splitting, or as mentioned before, it can sometimes be alluding to what is known as purple hydrogen.
- White hydrogen: this type of hydrogen is found in underground deposits, generated by natural geochemical processes inside the Earth's crust. While this is the main definition, some sources also describe white hydrogen as the result of the direct splitting of water molecules thanks to concentrated solar energy.

It is relevant to note that in December 2021 the European Commission released its legislative package on hydrogen and decarbonised markets, which consisted of three legislative proposals. Particularly, in the proposed Gas and Hydrogen Directive, legal definitions for renewable hydrogen and low-carbon hydrogen were stated that will hopefully clarify the role of hydrogen regarding the regulatory framework and prompt the development of the hydrogen market, infrastructure …

- Renewable hydrogen (as defined in the proposal directive to amend RED II): renewable fuels of non-biological origin and biomass fuels that meet a 70% GHG emission reduction compared to fossil fuels setting specific sub-targets for the consumption of renewable hydrogen (50% of total H_2 consumption for energy and feedstock purposes in industry by 2030 and 2.6% of the energy supplied to the transport sector).
- Low-carbon hydrogen: hydrogen, the energy content of which is derived from non-renewable sources, that meets a GHG emission reduction threshold of 70%.

Furthermore, it is pertinent to cite the EU Parliament, which states that:

The classification of different types of hydrogen would inter alia serve the purpose of providing consumers with information and it is not meant to stall the expansion of hydrogen in general.

> [Another matter at hand in this section is] *the urgent need for EU and international standards and certification*. [The EU Parliament] *stresses that the standardisation system needs to be based on a holistic approach and must be applicable to imported hydrogen; calls on the Commission to introduce a regulatory framework with robust and transparent sustainability criteria for the certification and tracking of hydrogen in the EU, taking into account its greenhouse gas footprint throughout the value chain, including transport, in order to also trigger investment in sufficient supplementary renewable electricity generation; also calls on the Commission to provide [...] a regulatory framework for hydrogen that ensures standardisation, certification, guarantees of origin, labelling and tradability across Member States*.

In this regard, it is relevant to mention the project CertifHy, which has enabled the elaboration of certification schemes in Europe (expected to go international), as well as the creation of a stakeholder platform.

Its aim is to promote the production, procurement, and use of "non-renewable", "renewable", and "low-carbon" hydrogen for all uses, supporting the growth of the H_2 market.

CertifHy^{TM} has developed guarantee of origin certificates, a system of electronic certificates that authenticates, for a certain situation, the quantity of hydrogen produced and the registered device used, as well as the process utilised. These GO certificates are kept in the CertifHy^{TM} Registry database. One of their features is the detachment from the location since a certain amount of H_2 can acquire the properties of the H_2 associated with the GO certificate.

The GO certificates are generated for each hydrogen quantity produced and registered, and this H_2 is tracked during its life cycle, meaning there is no double use within the registry.

The CertifHy^{TM} GOs consist of the elements in Figure 5, pictured below:

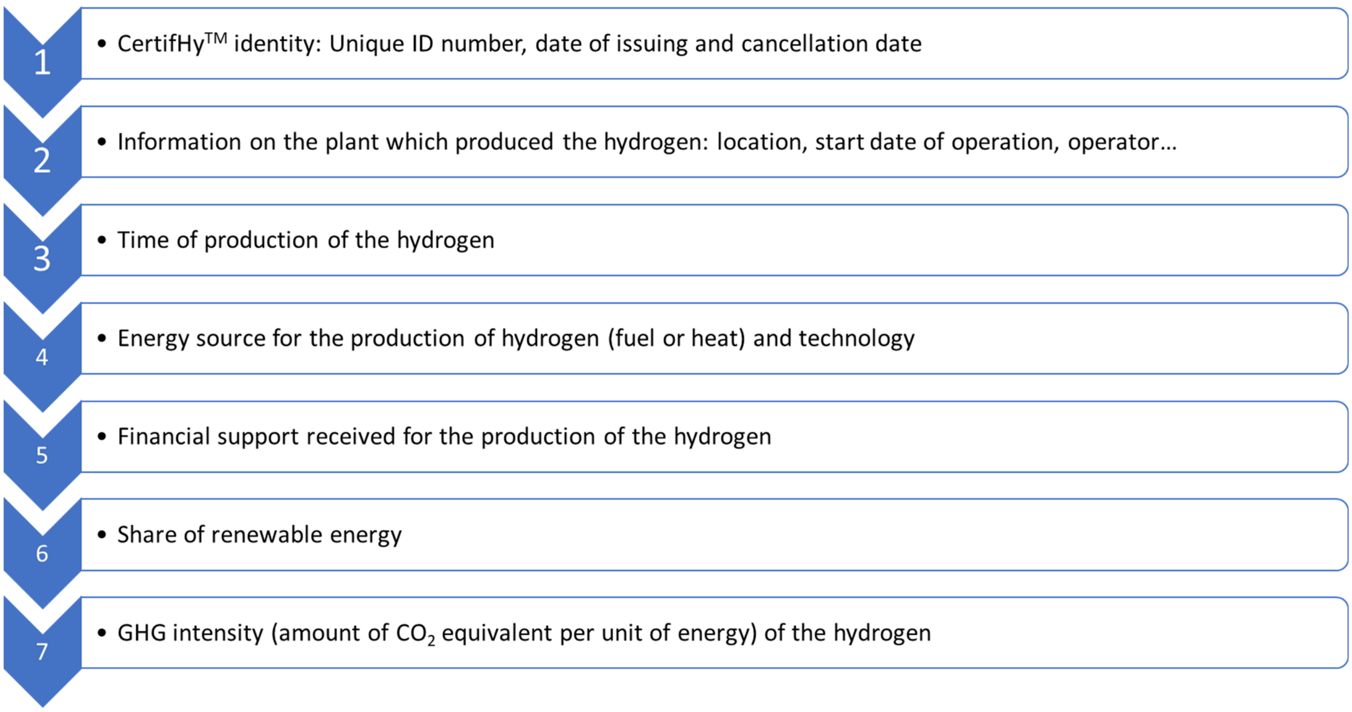

Figure 5. Content of the CertifHy^{TM} GOs [29].

These certificates can also have labels, particularly the "CertifHy^{TM} Green hydrogen" and the "Low-carbon hydrogen" labels.

Many advantages are linked to having a reliable certification system, as expressed in the CertifHy website. Some of them are:

- It incentivises the creation of a new business model through product differentiation.
- There is an increase in liquidity and transparency thanks to a globalised European market.
- It is a standardised solution recognised between the market players and makes it easy to trade.
- It provides trust to end consumers.
- It allows consumers to transfer value towards the production method they want to support.
- The use of renewable or low carbon H_2 can be independent from the location.
- It increases the role of hydrogen in the energy transition.
- It measures the impact of CO_2 emissions.
- Enables consumers disclosure.

About the certification itself, it is important to know about the GHG calculation and allocation.

CertifHy^{TM} performs a case study for each production technique (electrolysis, SMR+CCU, chloralkali, etc.) and develops a dedicated GHG allocation method, which is then used as a part of the CertifHy^{TM} scheme.

The concept of GHG intensity used is based on CO_2 emissions of the whole production trajectory ("well-to-gate") to produce hydrogen with a certain quality and pressure, including the emissions of transportation to the production site.

This project is a consortium [29] led by Hinicio, requested by the European Commission, and financed by the Clean Hydrogen Partnership.

Finally, this section tackles the concept of safety regarding hydrogen. The EU Parliament:

> *Highlights that safety protocols in demand sectors need to be updated continuously with regard to hydrogen use [. . .]* [and] *asks [. . .] that best-practice examples and a hydrogen safety culture be promoted throughout the EU*.

3.1.3. Ramping up Hydrogen Production

This section assesses several topics within the ramping up of hydrogen production.

First, and quite persistently, the EU Parliament asks for a regulatory framework for hydrogen and comments on the need to reduce the costs of hydrogen, particularly the EU Parliament:

> *Highlights that in order to ensure the internal hydrogen market functions well [. . .] a [. . .] regulatory framework for a hydrogen market should be [. . .] proposed by the Commission and calls on the Commission and the Member States to reduce regulatory and economic hurdles in order to foster a quick market uptake of hydrogen*.
>
> [This framework] *should be aligned with other relevant legislation [. . .]. The Commission* [must] *look [. . .] into the review of the Renewable Energy Directive, the Energy Taxation Directive and the ETS Directive in order to ensure a level playing field and a future-proof regulatory framework*.
>
> [Moreover, the EU Parliament] *believes that the EU gas market design and the Clean Energy Package could serve as a basis and example for the regulation of the hydrogen market*.
>
> *An adequate regulatory framework* [is a requisite, together with] *the necessary investments* [and competitive renewable energy, to make] *renewable hydrogen* competitive *before 2030*.

While very articulate, a few questions arise when reading this, such as: what are the regulatory and economic barriers to the hydrogen market? What characteristics should the regulatory framework have? How can the EU gas market design and the Clean Energy Package establish a basis for the hydrogen market?

The hurdles, for instance, are:

- Taxes and levies on renewable energy; the member states should reduce them in order to eliminate double charging of taxes and fees on electricity generated from hydrogen facilities.
- Missing regulation, poor regulatory environment, legal uncertainty, and inconsistency across countries.
- Issues regarding permits (for construction, deployment, operating . . .) due to the lack of H_2 experience of the permitting authorities and the missing procedures for this sector; also, unclear requirements.
- High investments needed and high costs.

Therefore, the regulatory framework for the hydrogen market should be able to overcome these barriers while also being:

> *Coherent, integrated and comprehensive, respecting the principles of proportionality, subsidiarity and better regulation*, [and allowing for the scaling up of the H_2 market].

Finally, it is time to answer the remaining question: what are the EU gas market design and the Clean Energy Package, and how can they serve the H_2 market?

The Clean Energy Package is a 2019 energy policy framework aiming to help decarbonise the European Union's energy system in compliance with the Green Deal objectives. This package comprises eight laws regarding subjects such as energy efficiency, energy performance in buildings, or electricity directive.

The EU gas market design, as well as the electricity market, has the goal of procuring an unbiased and non-discriminatory market environment to develop liquid wholesale markets. The experience from this market results in the identification of certain needs for the H_2 market, particularly regulatory principles such as third-party access, no discrimination, unbundling from vertically integrated activities, and transparency.

Moreover, the hydrogen regulatory framework can be based on the internal energy market for gas and electricity while also considering the particularities of the H_2 market.

It is important to note that the hydrogen infrastructure is bound to evolve as a monopoly, and the regulatory framework should reflect that. The hydrogen market should be developed together with the required infrastructure, and a dynamic regulation could incentivise investments for this while also being flexible to adapt to the different developments of the member states in terms of hydrogen market.

Afterwards, the EU Parliament:

> *Encourages the Commission and the Member States to devise specific solutions in order to ramp up hydrogen production in less connected or isolated regions such as islands, while ensuring the development of related infrastructure, including by repurposing it*.
>
> [Moreover, it] *stresses the potential to convert some existing industrial sites into renewable hydrogen production facilities, planning such conversions of industrial sites with the workers and their trade unions*.

The EU has already taken an interest in islands, as proven by Clean Energy for EU islands, a secretariat driven by the European Commission that serves as a platform for the clean energy transition of the EU islands. It provides assistance and information on policy, regulation, etc., including a national scope for the countries with inhabited islands, necessary given the inherent challenges islands face, such as unsteady seasonal demand due to economies based on tourism, lack of security supply, fuel import dependency, lack of system stability, and limitations of energy interconnections [30].

Changing the subject, another message is that the EU Parliament:

> *Welcomes the ambitious goals of increasing the capacity of electrolysers and renewable hydrogen production* [and] *calls on* [this organisation] *to develop a roadmap for the deployment and upscaling of electrolysers and to forge partnerships at the EU level to ensure their cost-effectiveness*.

In the Commission's 2020 hydrogen strategy, it was stated that the renewable hydrogen electrolyser capacity in the EU wanted by 2024 was 6 GW (1 million tonnes of renewable hydrogen associated, where the current hydrogen production in Europe is 18–20 million tonnes per year [3]). Therefore, it is in that document that the Commission discusses the scaling up of production.

However, a month after the Parliament's H_2 strategy was released, in June 2021, Delta-EE, a global hydrogen intelligence service, announced that the electrolysis capacity reached by 2050 would be 2.7 GW, therefore, missing the 2024 target.

Nevertheless, Delta-EE later issued a whitepaper in March 2022 expecting a fulfilment of the 2024 target. Moreover, as previously explained, there was a joint declaration signed within the European Electrolyser Summit in May 2022. In this joint declaration, the participants committed to a tenfold increase in electrolyser capacity; also, it was acknowledged that to produce 10 m tons of renewable H_2, approximately 90–100 GW of electrolyser capacity would be needed. That implies a considerable increase, although in the short term, the electrolyser manufacturers in Europe expect a manufacturing capacity of 17.5 GW.

This escalation happened in the context of the RePowerEU communication, previously reviewed.

The EU Parliament also expresses its views on fossil-based hydrogen and low-carbon hydrogen.

> [Particularly], *recognises that there will be different forms of hydrogen on the market, such as renewable and low-carbon hydrogen, and underlines the need for investment to scale up renewable production [. . .] while recognising low-carbon hydrogen as a bridging technology in the short and medium term*.

> [The Parliament also] *calls on the Commission to assess approximately how much low-carbon hydrogen will be needed for decarbonisation purposes until renewable hydrogen can play this role alone*.

> [That being said, the Parliament] *stresses the importance of phasing out fossil-based hydrogen as soon as possible* [and] *urges the Commission and the Member States to [. . .] start planning that transition [. . .] so that the production of fossil-based hydrogen starts decreasing swiftly, predictably and irreversibly*.

> [It also] *highlights that effective support measures should be directed at the decarbonisation of existing fossil-based hydrogen production [and] urges that measures aimed at the development of the European hydrogen economy should not lead to the closure of the fossil-based hydrogen production sites, but to their modernisation and further development*.

Completely eliminating fossil-based hydrogen is not an easy task given that, currently, it represents 95% of the hydrogen produced in Europe. On the other hand, low-carbon hydrogen represents the 0.7% but is considered to be a bridging technology that will contribute to the transition to a fully renewable hydrogen use. While the Commission is yet to give an exact assessment on low-carbon H_2, it has granted it its role in the Hydrogen and Decarbonised Gas Package, issued in December 2021, although including it in a broader category: low-carbon fuels.

In addition, in this section, the EU Parliament:

> *Underlines the role that environmentally safe carbon capture storage and utilisation (CCS/U) can play in reaching the European Green Deal objectives and supports an integrated policy context to stimulate the uptake of environmentally safe CCS/U applications [. . .] in order to make heavy industry climate-neutral where no direct emission reduction options are available, noting the need for research and development in CCS/U technologies*.

Additionally, it is important to be aware of the role of renewable energy in the hydrogen strategy, and that is why the European Parliament:

> *Underlines that a hydrogen economy requires significant additional amounts of affordable renewable energy and the corresponding infrastructure for [. . .] [its] production [. . .]*

> *and its transport to hydrogen production sites and [...] to the end users; [also] calls on the Commission and the Member States to start the roll-out of sufficient supplementary renewable energy capacity to supply the electrification process and the production of renewable hydrogen*.
>
> [It also] *considers that the deployment of appropriate renewable energy capacity in proportion to the need for renewable hydrogen can help to avoid conflict between the capacity required for electrification, electrolysers and other purposes and the need to meet the EU's climate goals; welcomes, in that regard, the Commission's plans to increase EU renewable energy target for 2030 and its proposed strategy on offshore renewable energy*.
>
> [Moreover, it stresses that] *renewable hydrogen can be produced from several renewable energy sources such as wind, solar and hydropower,* [and that ... brownfields have potential ...] *to provide space for renewable energy production;* [also, it] *invites the Commission [...] to assess how offshore renewable energy sources could pave the way for the wide development and uptake of renewable hydrogen*.

The premise of this subdivision is straightforward: an increase in renewable hydrogen production implies an increase in renewable energy capacity.

Some questions that might come to mind are: how much renewable energy capacity is enough to cover both the electrification process and the renewable hydrogen production? What is the EU renewable energy target for 2030?

Within the climate target plan, the goal of reaching the target of a 40% GHG emissions reduction by 2030 (compared to 1990) is increased.

The Commission's objective is to achieve a 55% GHG emissions reduction by 2030 (also compared to 1990), and that means that the share of renewable electricity produced in the EU is bound to reach at least 65%, and the gross final consumption share of renewable electricity would reach almost 40%. This renewable electricity will help decarbonise many sectors through direct electrification and also through renewable hydrogen.

Next, the Parliament comments on the strategy on offshore renewable energy and the assessment of its role in relation to renewable hydrogen.

This strategy is in line with the 55% GHG emissions reduction previously mentioned since offshore renewable energy will be part of the renewable energy installed to reach the targets.

Offshore renewable energy encompasses different technologies, such as:

- Offshore wind technology, with bottom-fixed wind turbines;
- Floating offshore wind technology;
- Tidal energy technology;
- Wave energy technology;

and less developed:

- Algal biofuels technology;
- Ocean thermal energy conversion technology;
- Floating photovoltaic technology.

As of November 2020, the date the "EU Strategy to harness the potential of offshore renewable energy for a climate neutral future" was issued, the installed offshore wind capacity was 12 GW.

By 2030, the goal is to have at least 60 GW and 1 GW installed of wind capacity and ocean energy capacity, respectively. By 2050, those numbers could increase, achieving 300 GW and 40 GW (respectively) of installed capacity. Within this strategy, it is estimated that almost EUR 800 billion will be required.

The increase in renewable energy available can contribute to indirect electrification through hydrogen and synthetic fuels. Furthermore, in the Commission's hydrogen strategy, the goal is to have 40 GW of electrolysis installed capacity, thus, there is a need for renewable energy production.

One possibility to deliver the energy produced offshore to the mainland is through hydrogen produced on site and transported through hydrogen pipelines or by ship.

This opportunity has not gone unnoticed by companies such as Siemens Gamesa and Siemens Energy, who are already developing an approach to integrate an electrolyser into an adapted offshore wind turbine to produce renewable hydrogen. The system consists of their most powerful wind turbine, an electrolyser fed with the electricity produced by the turbine and water obtained directly from the sea and treated in a desalination process and a H_2 dryer to purify the hydrogen.

This decentralised model entails a CAPEX reduction, an increase in the system efficiency, and an increase in the plant load factor in comparison to a centralised model (electrolyser close to consumer facilities, not integrated in the wind turbine).

Another example of this sector's growth is the case of the North Sea and its vast potential in terms of renewable energy production, particularly offshore wind energy and hydrogen production. The research program North Sea Energy studies its potential to be an integrated system and is developing multiple research and pilot projects, such as the PosHYdon project in the Netherlands, which combines offshore wind, offshore gas, and offshore hydrogen.

Changing to a different subject, in this section, the Parliament also comments on the taxes and levies associated with the hydrogen sector in Europe, particularly:

> *Calls for the revision of the Energy Taxation Directive; calls on Member States to consider reducing taxes and levies on renewable energy across the EU [...] to eliminate double-charging of taxes and fees on electricity generated from hydrogen facilities [...] and to strengthen financial incentives to produce renewable energy, while simultaneously further working towards the phase-out of fossil fuel subsidies, tax and levy exemptions*.

The European Parliament demands a revision of the Energy Taxation Directive, adopted in 2003, since this directive is not up to date with the hydrogen technologies and market, nor is it aligned with the EU climate and energy policies.

The proposal for a revision of the Energy Taxation Directive was issued two months after the Parliament's hydrogen strategy, in July 2021.

The principal modifications were:

- A new tax rate structure is established using the energy content and environmental performance of the electricity fuels as the criteria, not the volume. The most environmentally damaging fuels sustain the highest minimum rates.
- The minimum rates are to be adapted annually to reflect the most recent prices.
- The taxable base is being extended; more products are included, and some of the exemptions and rate reductions are removed.
- Kerosene and heavy oil used for air and maritime transport within the EU are no longer exempt from energy taxation.

These alterations will hopefully help obtain a better indication of the environmental impact of fuels and electricity and allow for cleaner decisions.

Another aspect also contemplated in the revision is the double taxation of electricity, and this is particularly significant for electricity generated from hydrogen facilities, as remarked by the Parliament.

In the revision, it is tackled, deeming that electricity storage or electricity transformation facilities could be regarded as redistributors when supplying electricity to avoid it.

The Parliament also considers the member states' different situations regarding their hydrogen economies:

> *The transition to a climate-neutral energy system should be planned carefully, taking into account [...] starting points and infrastructure, which may differ across the Member States [...]. The Member States should be flexible when designing [...] State aid measures, for the development of their national hydrogen economies; also asks*

the Commission [. . .] to provide more information on planned differentiation and the flexibility of support measures.

Finally, in this section, the topic of resources emerges. The Parliament:

Underlines the significant amount of natural resources, such as water, needed for hydrogen production and the problems this may cause for water-scarce regions in the EU; stresses the importance of increasing resource efficiency, minimising the impact on regional water supplies, ensuring the careful management of resources and land use for the production of hydrogen and avoiding any contamination of water, air or soil, deforestation or loss of biodiversity, as a result of the hydrogen-related production chain.

The resource depletion is a remarkably interesting topic that is relevant to every technology and sector and is a broad subject that can be covered on its own.

In this project, however, the focus is on hydrogen production and the resources and materials associated with it, particularly, as the Parliament mentions, water.

Water scarcity is increasingly becoming a concern for Europe, and it is growing worse as a consequence of climate change. According to a report issued by the European Environment Agency (EEA) in October 2021 [31], currently, during an average year, approximately 20% of European territory is affected by water stress.

Water scarcity and droughts have a higher impact on southern Europe, as seen in Figure 6. This Figure, taken from the EEA report, shows the projected change in annual and summer precipitation in Europe in the 2071–2100 time span.

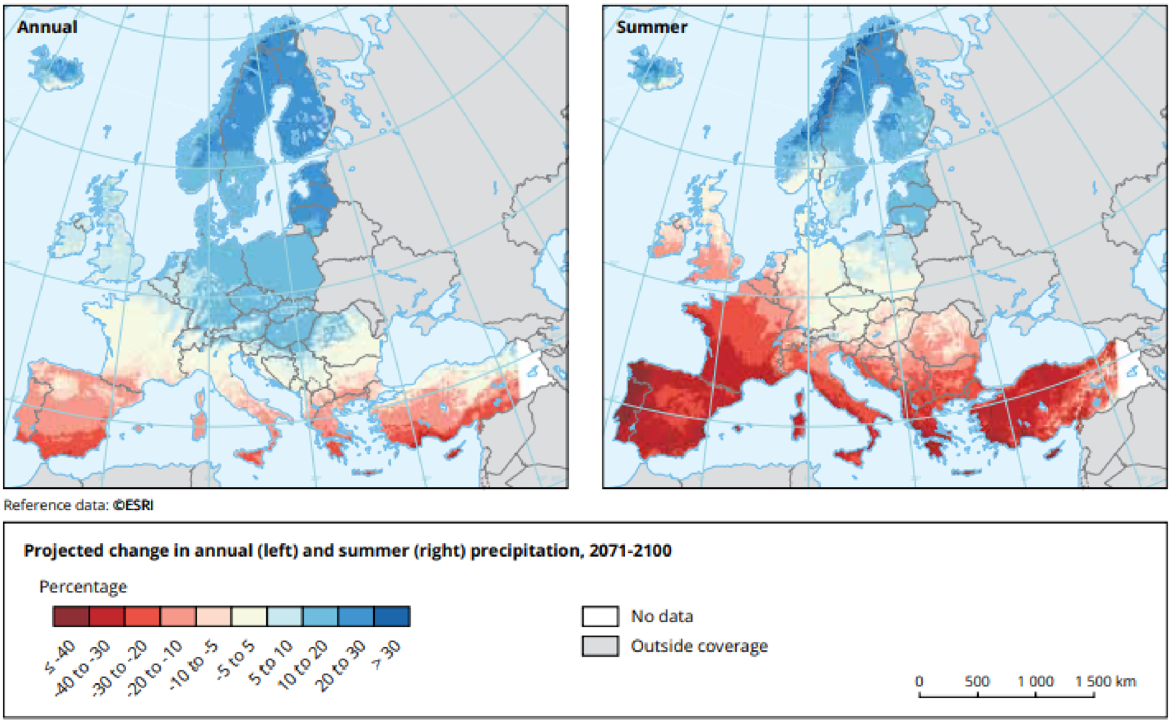

Figure 6. Projected change in precipitation in Europe [31].

Again, it is a vast subject and could be talked about exhaustively, but a brief conclusion could be that there is a need to enhance water management and make it more efficient, avoiding water scarcity and pollution, although it is explained in detail in the report previously mentioned. It is pertinent to note that there are associations, such as Water Europe, water directives, and even drought management plans by some member states.

Water consumption for hydrogen production differs depending on the technology and the energy source. Hydrogen produced through SMR requires water as feedstock; particularly, when using natural gas, 4.5 kg of water are needed per kg of H_2 just as feedstock, although reaction efficiency, consumption for cooling, and other uses make this number bigger.

Hydrogen produced through electrolysis requires 9 kg of water per kg of H_2 produced, but again, that is from the stoichiometric point of view, since reaction efficiency and other uses increase this ratio. Furthermore, the electricity fed to the electrolyser also has water consumption with it (cooling, mining, refining, etc., including renewable energy).

Water consumption also depends on the end use of H_2. If the hydrogen is consumed in a fuel cell for instance, then the by-product is water, although it is not clear whether this water is returned to the body of water it belonged to. However, if the H_2 is used in chemical synthesis, the water is not entirely recovered.

As previously commented, the European Union's goal is to produce 10 million tons of renewable H_2 per year by 2030 (where the current hydrogen production in Europe is 18–20 million tonnes per year [3]). In IRENA's 2020 report, "Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 °C climate goal", it is estimated that the water consumption of the production of renewable hydrogen is approximately 18 to 24 kg per kg of H_2, and that is without taking into account the electricity source. Making a simplistic calculation using the ratio of 20 kg H_2O/kg H_2, reaching the EU's goal of 10 million tons of renewable H_2 per year would require 200 million tons of water.

One interesting solution to this issue is the desalination of salt water, which accounts for 99% of the planet's water. The main desalination process currently is reverse osmosis and, while this tackles the resource aspect, the ratio of "freshwater obtained/saltwater consumed" is up to 0.5, and adding desalination increases the complexity and energy required of a project.

3.1.4. Citizen Engagement

Regarding citizen engagement, the EU Parliament underlines that:

> [It] will play an important role in the implementation of [. . .] [the] *energy transition* [and that it is important to ensure] *that all stakeholders share the costs and benefits in an integrated system*.
>
> [It also states] *that renewable energy communities can be involved in the production of hydrogen and recalls the obligation to provide them with an enabling framework in accordance with Directive (EU) 2019/944 and requests that they benefit from the same advantages as other stakeholders*.

The significance of citizen engagement is also expressed in the Clean Hydrogen JU's Work Programme 2022, particularly in the call for proposals in "Public understanding of hydrogen and fuel cell technologies". It is stated that public acceptance of the hydrogen technologies and applications is fundamental for the transition to a H_2 economy, and this organisation asks for projects that analyse, assess, and enhance the engagement of citizens.

Renewable energy communities are legal entities (associations, partnerships . . .) that allow citizens to participate and invest in energy assets and access the energy markets with similar conditions to other market actors. These communities, in line with the directive previously mentioned, can participate actively in the market by generating, consuming, sharing, selling, or storing electricity, and the citizens benefit from lower energy prices.

They are also a way to earn public acceptance for renewable energy projects.

Regarding the guidance and assistance for these organisations, the European Commission with funding from the Parliament has created the Energy Communities Repository, which was launched in April 2022.

Furthermore, in the revision of the Renewable Energy Directive the renewable energy communities and citizens within them are encouraged to develop, involving them in the clean energy transition.

> [Afterwards, the Parliament] *stresses that in order to have a properly functioning EU hydrogen market, people with specialised skills are needed, especially with regard to safety and underlines the necessity of a [. . .] training system; calls on the Commission to adopt*

> *an action plan aimed at guiding Member States to develop [...] training programmes for workers, engineers, technicians and the general public, and to create multi-disciplinary teaching programmes for economists, scientists and students [...]* [also] *calls for the launch of an EU initiative focused on employment, training and development for women*.
>
> [It also] *stresses the importance of preserving and tapping into the potential of workers with technical skills employed in existing industries, and recalls the right of workers to be trained and upskilled during working hours with their wages guaranteed*.

In the pasts, projects regarding the safety training topic were developed. In the European context, for instance, HyResponse was conceived from 2013 to 2016. This project's aim was to create a hydrogen safety training platform and to instruct European first responders to assess situations, make decisions, and be prepared for the emergency response level in the event that an accident happened on site. The guidance was focused on hydrogen safety regarding all aspects: production, distribution, storage, fuel cell cars, buses and forklifts, refuelling stations, fuel cells for combined heat, and power, etc.

Following the steps of HyResponse and within the context of FCH JU (Clean Hydrogen Partnership), HyResponder was created with the objective of developing a "train the trainer" programme regarding hydrogen safety, also for responders in the EU. Beyond the European Union, there are more organisations committed to this subject, such as HySafe, the International Association for Hydrogen Safety.

Moreover, the EU (FCH 2 JU) also started the European Hydrogen Safety Panel, and now, it will help ensure hydrogen safety in projects and programmes and promote a hydrogen safety culture.

Finally, in this section, the EU Parliament:

> *Calls on the Commission to produce data on the possible impacts, opportunities and challenges [...] in relation to the scaling-up of hydrogen [...]* [and] *suggests the launch of an EU skills partnership on hydrogen under the Pact for Skills*.

The Pact for Skills was established in November 2020 and is a knowledge, resource, and networking hub for companies, partnerships, and other organisations to develop skills in Europe. Regarding the commitments under this pact, some European industrial partnerships are found, such as: the pact for skills in construction, the aerospace and defence skills partnership, or the skills partnership for offshore renewable energy. Therefore, it is appropriate for a skill partnership on hydrogen to be launched.

3.1.5. Hydrogen Infrastructure

In the hydrogen infrastructure section, a few topics are discussed.

First, the EU Parliament:

> *Emphasises the urgent need to develop infrastructure for hydrogen production, storage and transport, to incentivise adequate capacity-building, and to develop demand and supply in parallel [...]* [also] *notes the [...] benefits of combining hydrogen production and infrastructure with other aspects of flexible, multi-energy systems such as waste heat recovery from electrolysis for district heating*.

The example given by the Parliament, waste heat recovery from electrolysis for district heating, is actually an idea already being explored. As it is further explained in the paper, "Power to hydrogen & district heating" [32], a considerable amount of waste heat is produced in the electrolysis process, although the exact amount depends on the technology used; according to this paper, the concept of waste heat potential encompasses process excess heat, product gases and cooling of stack, convection, and radiation losses and it can constitute up to 29% of the energy input, and this heat could be used, for instance, for preheating the return line of the district heating network. It contributes to the energy efficiency of the system, and it is an application worth considering since the electrolysis capacity is bound to grow; again, it is further analysed (technologically, economically, etc.) in the paper mentioned.

Next, the Parliament:

> *Welcomes the Commission's proposal to amend the TEN-E Regulation and appreciates the inclusion of hydrogen as a dedicated energy infrastructure category.*
>
> *Notes that [...] the planning, regulation and development of infrastructure for the transmission of hydrogen over longer distances and storage, as well as adequate financial support for that infrastructure, should already be being undertaken [...] welcomes [...] the future inclusion of hydrogen infrastructure in EU plans, such as the Ten-Year Network Development Plans.*

The Trans-European Networks for Energy was first released in 2013 to stipulate the guidelines for cross-border energy infrastructure in Europe, establishing nine priority corridors (divided geographically) that connect regions, supporting the development of their oil, gas, and electricity infrastructure, and also three priority thematic areas: smart grid deployment, electricity highways, and the cross-border carbon dioxide network. The Commission, as the Parliament indicates, proposed a revision in December 2020. The aim of this revision was to adapt the regulation to the Green Deal objectives by supporting infrastructure for clean energy technologies, including hydrogen, and doing the opposite for fossil fuels.

This revised regulation is contributing to the elaboration of the regulatory framework and planning of the hydrogen infrastructure, also tackling transport and electrolysis, which will simplify bureaucratic operations and, therefore, stimulate investments.

This section also mentions the Ten-Year Network Development Plan (TYNDP), which is a programme developed by the European Network of Transmission System Operators for Electricity (ENTSO-E) every two years to regulate the European electricity transmission network, and it is relevant to the development of infrastructure.

> [The Parliament also] *notes that [...] hydrogen assets may be newly constructed or converted from natural gas, or a combination of the two.* [It] *encourages the Commission and Member States to make a science-based assessment of the possibility of repurposing existing gas pipelines for the transport of pure hydrogen and the underground storage of hydrogen and it notes that repurposing ... gas infrastructure ... could maximise cost efficiency, minimise land and resource use and investment costs and minimise the social impact,* [and could also] *be relevant for the use of hydrogen in the priority sectors of emission-intensive industries [...] calls on the Commission to assess where hydrogen blending is currently used [...] with a view to identifying infrastructure needs.*

It is often commented that the gas infrastructure can be converted to integrate transportation and storage of hydrogen with fewer difficulties and inconveniences than other options.

This topic is developed in the GIE position paper: Regulation of Hydrogen Infrastructure. GIE is the acronym for Gas Infrastructure Europe, the association that represents the gas infrastructure operators that manage gas transmission networks, storage systems, and LNG terminals.

Within the context of the Green Deal and the 55% GHG emissions reduction target, and given the similarities between hydrogen and natural gas, GIE members are committed to tackle these goals through hydrogen.

The hydrogen market is bound to develop, and the increase in demand implies an increase in transport, storage, and import and export infrastructure to manage the large volumes of H_2. This infrastructure can be newly built in the cases that are economical, and it can also be a result of retrofitting and repurposing the existing gas infrastructure. The second option is linked to time and cost savings, the reduction in land resource use, and the increase in social acceptance, taking advantage of the fact that gas infrastructure is fitting for this conversion.

The current European gas infrastructure is well developed and has a wide scope, allowing for the safe management of hydrogen and for the decarbonisation of the energy system when used for hydrogen transportation and storage. An economic assessment by the European Hydrogen Backbone Initiative shares the following figure: the existing gas infrastructure can be repurposed at 10–35% of the cost of building the H_2 infrastructure from scratch.

Regarding underground storage, which is an option that enables seasonal storage and provides security in supply, the options considered are salt caverns, porous rock storage sites, and aquifers, as explained in the storage section of this project. The first can be entirely filled with H_2 with no reactivity issues, but the last two require retrofitting to blend H_2 with natural gas.

Finally, in relation to the LNG terminals in this paper, their suitable role is remarked upon since they can be retrofitted and repurposed, allowing for the import and export of hydrogen, being able to receive different H_2-based energy carriers.

Afterwards the Parliament:

> *Stresses the importance of [. . .] integrated network planning with the guidance of public bodies like the European Union Agency for the Cooperation of Energy Regulators (ACER) and the participation of stakeholders and scientific bodies; suggests, in that regard, that cost-benefit calculations for the location of renewable hydrogen production, transport and storage infrastructure be made and that the need to build new ones be examined [. . .] highlights the financial benefits of placing hydrogen production facilities close to renewable energy production sites or the same site as demand facilities*.

Indeed, ACER is one of the principal assisting organisations regarding the European energy market and network, aiding the regulatory authorities of the different member states and coordinating them. This body also collaborates on the elaboration of network rules, monitors the energy market, and reports on that topic, among other tasks.

There are still barriers to overcome, and particularly in this section, the cost is discussed. It was already said that electrolysis is not the cheapest option currently, but it is being promoted to be the main one in Europe and there is a clear need for driving down the costs. In addition to research and development regarding the technology, there is the possibility of choosing the location favourably, which might mean either placing the H_2 production site close or in the renewable energy production site or placing it near/in the demand sites. This is a way to make the most of the resources already available and/or reduce the cost and complexity of the distribution system.

Making a distinction, these options can be named "centralised production" and "distributed production". Centralised hydrogen production—producing all the H_2 in one facility near or in the same site as the renewable energy production site—has lower production costs not only because the electricity is produced in close proximity to the facility but mainly because of the economy of scale. However, the demand or end-use sites might be far away from the facility, therefore, increasing the transportation costs.

For distributed production—producing H_2 where the demand or end-use sites are—this is the opposite, and so are the conclusions: the distribution costs are lower but the production costs soar.

Both options are feasible, and some may be more adequate in a certain situation; for instance, distributed or on-site production can be suitable for an industry with a high volume of hydrogen consumption.

After that, the European Parliament:

> *Underlines the necessity of regulating hydrogen infrastructure and the need to uphold unbundling as a guiding principle for the design of hydrogen markets [. . .]* [since it] *plays a key role in ensuring that innovative new products are put on the energy market in the most cost-efficient manner*.

The principle of unbundling in network systems consists of the separation of the activities that entail competition from those for which competition is not possible or permitted. In the energy context, an example of the first kind is the production and purchase of energy, and an example of the second is energy distribution; actually, in Europe, the gas and electricity networks are monopolies.

The reason behind this principle is that a company that operates in a competitive activity cannot participate in the related monopolistic activity, and this can be applied in various degrees.

In terms of energy (electricity, gas, and eventually, hydrogen), the network and distribution system are considered crucial, and access to it must be fair and non-discriminatory. If unbundling were not present, a company, for instance, in the distribution system, can act according to its own interests regarding its activities in production or consumption and can work against a competitor by denying access.

Finally, in this section, the EU Parliament:

> *Stresses the strategically essential role of multimodal maritime and inland ports as innovation pools and hubs for the import, production, storage, supply and utilisation of hydrogen; underlines the need for space for and investment in port infrastructure*.

Ports are an essential part of hydrogen distribution and trade but are also significant participants in the adoption of hydrogen technologies, accelerating their own decarbonisation.

One example of the incorporation of hydrogen technologies is the H2Ports project, co-founded by the European Union through Fuel Cells and Hydrogen 2 Joint Undertaking, which has the goal of evaluating and demonstrating the use of fuel cells port equipment. It takes place in the Port of Valencia (Spain) and will validate the use of the three applications: a FC-based reach stacker, a FC-based yard tractor, and a hydrogen mobile supply station in the daily, real port operations.

A second example is the Global Ports Hydrogen Coalition within the Clean Energy Ministerial Hydrogen Initiative (CEM H2I) coordinated by the IEA. The CEM H2I is an initiative by which various governments aim to boost the deployment and commercialisation of hydrogen and fuel cell technologies, and the Global Ports Hydrogen Coalition contributes to that goal by enhancing collaboration in projects to scale up the use of hydrogen-based fuels in ports.

3.1.6. Hydrogen Demand

This next section delves into hydrogen demand.

First, the EU Parliament:

> *Acknowledges that the focus on hydrogen demand should be on sectors for which the use of hydrogen is close to being competitive or that currently cannot be decarbonised using other technological solutions [. . .] the main markets [. . .] are industry, air, maritime and heavy-duty transport; believes that, for these sectors, roadmaps for demand development, investment and research needs should be established*.

> [Also] *agrees with the Commission that demand-focused policies and clear incentives for the [. . .] use of hydrogen [. . .] in order to trigger the demand for hydrogen—such as quotas for the use of renewable hydrogen in a limited number of specific sectors, European Investment Bank guarantees to reduce the initial risk of co-investments until they are cost-competitive, and financial tools, including Carbon Contracts for Difference (CCfD) for projects using renewable or low-carbon hydrogen—could be considered*.

As mentioned, renewable hydrogen has high costs that halt its competitiveness and progress, and although costs are expected to decrease, this development needs to be paired with financial support and incentives.

One of the options proposed is quotas for the use of renewable hydrogen in some sectors and applications outside of the EU Emissions Trading System.

In the paper "Analysing the impact of a renewable hydrogen quota on the electricity and natural gas markets" [33], the renewable hydrogen quota is a policy tool to impel the use of renewable hydrogen, and in this study, it is imposed on the demand side. The conclusions of this study indicate that the implementation of this quota would lead to an increase in renewable energy capacity, an increase in electricity price, and a decrease in the prices in the gas market.

The other example given is Carbon Contracts for Difference (CCfD), a funding mechanism through which governments can give investors a guarantee on a price that rewards CO_2 emission reductions, a price different from what is established in the EU Emissions Trading System. The goal is for this to be an incentive to accelerate investments in low-carbon or renewable energy projects. Nevertheless, it is important to note that they might produce distortions on the emissions market since they can disrupt the free price formation.

Moreover, the Parliament adds that:

> [There is a] *need to ensure that the compensation remains proportionate and to avoid the duplication of subsidies for both production and use, the creation of artificial needs and undue market distortions*.

Subsequently, the Parliament expresses its interest in the use of hydrogen in the industry:

> *Urges the Commission to promote lead markets for renewable hydrogen technologies and their use for climate-neutral production—especially in the steel, cement and chemical industries—as part of the update and implementation of the New Industrial Strategy for Europe; calls on the Commission to assess the option of recognising steel produced with renewable hydrogen as a positive contribution to meeting fleet-wide CO_2 emission reduction targets; further urges the Commission to soon come forward with an EU strategy for clean steel*.

The EU industrial strategy was already tackled, so in this section, the main character is steel, particularly green or clean steel [34].

The first matter to elaborate on is the concept of clean steel itself. The steel industry can be decarbonised in various ways: using carbon capture and storage (CCS) or by using biomass as fuel and as a reducing agent instead of coke or electrification. Within the last option, hydrogen-direct reduction is the principal path taken by steel companies in Europe.

For context, 5.7% of the total EU GHG emissions are a result of the EU steel industry, making this sector a considerable target for decarbonisation.

According to the European Steel Association (EUROFER), which has even proposed a Green Deal on steel, the hydrogen strategy is welcomed in the sector since the transition to a zero or low-carbon steelmaking process would require around 5.5 million tonnes of H_2. Having a clear hydrogen strategy and strengthening the hydrogen economy and market in Europe are key to maintaining Europe's technological leadership and also establishing the European industry as a reference in decarbonisation while still being competitive.

Clean steel, while more expensive to produce, will result in environmental benefits (especially CO_2 emission reduction) and regional synergies since the H_2 network or hub created for a steel plant can incorporate other consumers and bring on new jobs and projects.

One month after the release of the Parliament's hydrogen strategy that is being analysed, the EU Clean Steel Partnership was founded. Shortly after, its Strategic Research and Innovation Agenda (SRIA) was issued.

In this document, it is stated that this partnership aims to contribute to reaching the Green Deal and Paris Agreement targets by reducing steelmaking emissions and also contribute to a circular economy in the EU. The partnership's general objective is also defined, which is to develop technologies to reduce the CO_2 emissions linked to steel production by around 80–95% of the emissions level in 1990; this objective is to be reached without compromising the sector's competitiveness. The complete approach can be read in the agenda itself, including context, ambitions, and expected impacts.

Finally in the hydrogen demand section, H_2 for transport is tackled. The EU Parliament:

> *Recalls that the transport sector is responsible for a quarter of CO_2 emissions in the EU [. . .] and underlines the potential of hydrogen to be one of the instruments used to reduce CO_2 emissions in transport modes, in particular where full electrification is more difficult or not yet possible*.

As commented by the Parliament, full electrification is one option to decarbonise the transport sector, but it is not possible for all types of transport. Aviation, maritime, and heavy-duty transport are difficult or impossible to be electrified currently.

> [Also] *underlines [. . .] the importance of revising the TEN-T (trans-European transport network) Regulation and the Alternative Fuels Infrastructure Directive to ensure the availability of publicly accessible hydrogen refuelling stations [. . .]* [and] *welcomes the Commission's intention to develop hydrogen refuelling infrastructure under the Sustainable and Smart Mobility Strategy*.

> [Moreover, the Parliament] *underlines that hydrogen's characteristics make it a good candidate to replace fossil fuels [. . .]* [and] *stresses that the use of hydrogen in its pure form or as a synthetic fuel or biokerosene is a key factor in the substitution of fossil kerosene for aviation [. . .] stresses that stronger legislation is needed to incentivise the use of zero-emission fuels*.

> [Finally], *calls on the Commission to increase research and investment within the framework of the Sustainable and Smart Mobility Strategy*.

The Trans-European Transport Network Regulation (TEN-T) is a policy that handles the development of transport networks, routes, terminals, etc., in Europe. It also defines requirements for the infrastructure in terms of quality, safety, or environmental impact for instance and incentivises sustainability and innovation.

Its network development can be divided into "Core Network" and "Comprehensive Network"; the first one, to be finished by 2030, covers the key connections (identifying nine core network corridors), while the second, to be finished by 2050, contains the rest of the regions and connections.

However, these guidelines were first issued in 2013 and do not reflect the current situation and targets and, as the Parliament remarks, did not include hydrogen infrastructure. The Commission itself has recognised the need for a revision of this policy to keep up with new technologies and sustainability objectives such as the European Green Deal goals. Subsequently, in April 2019, the review process commenced, and the revised guidelines were released in December 2021 by the Commission.

Some of the revised topics are: utilisation of innovative technology, the demand for certain cities to have urban mobility plans that are sustainable, and for climate-proofing of projects, among many more. It is pertinent to remark on the requirement to develop refuelling and charging infrastructure for alternative fuels applications, as asked by the Parliament and in agreement with the Alternative Fuels Infrastructure Directive. There are new milestones as well and a new phase, the "Extended Core Network, to be finished by 2040"; the new network layout can be seen in Figure 7 while being compared with its previous version.

Currently, the European Council and Parliament are in the midst of agreeing on the final proposed regulation, having released a briefing in March 2022, in which it is indicated that there are still a few steps until it is adopted.

The Parliament also mentions the Alternative Fuels Infrastructure Directive, which dates back to 2014 and aims to establish measures for the development of alternative fuel infrastructure, setting out requirements and technical specifications for said infrastructure. The alternative fuel concept includes hydrogen, but the directive did not obligate the member states to include hydrogen refuelling stations in their national policy frameworks.

In the Commission's "Fit For 55" package presented in July 2021, there was a proposal to revise this directive and convert it to a regulation. This proposal, according to the March 2022 briefing on its evolution, is awaiting committee vote. Some of the most relevant modifications regarding the hydrogen subject are the mandatory targets for hydrogen refuelling points and overall infrastructure.

The revision of the Alternative Fuels Infrastructure Directive was actually already alluded to in the Commission's Sustainable and Smart Mobility Strategy in 2020, which was also mentioned by the Parliament as it will indeed be an instrument to reach the EU's sustainability targets and include hydrogen infrastructure as well.

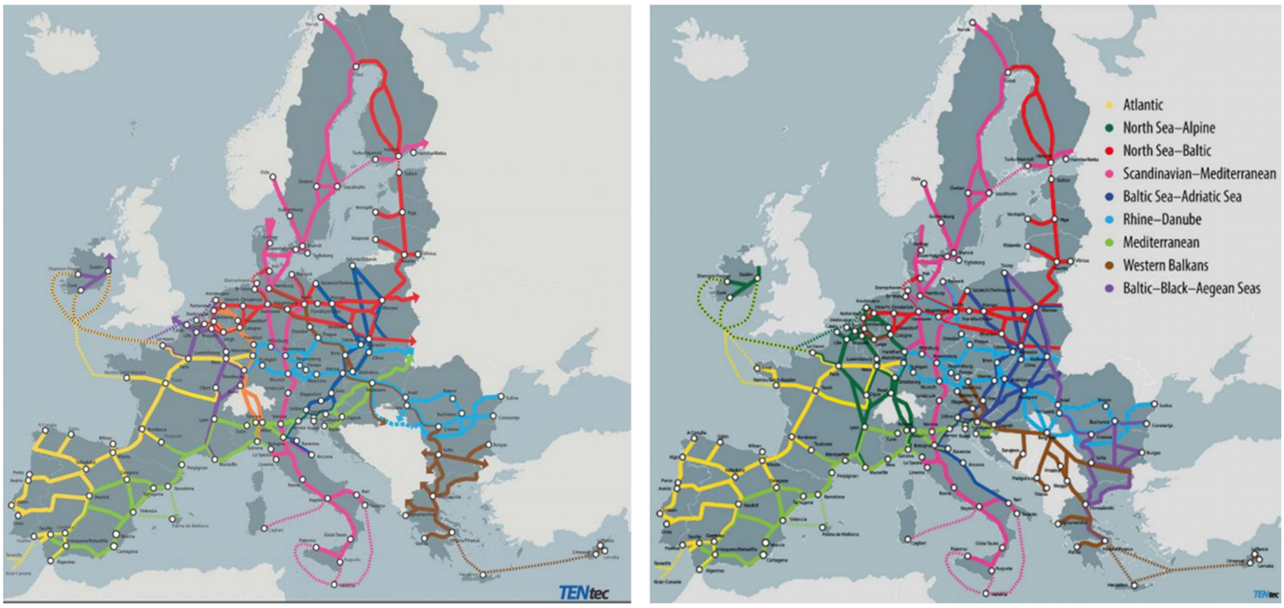

Figure 7. TEN-T network layout in the 2013 version [35] (**left**) and revised (2021) version [36,37] (**right**).

3.1.7. Research, Development, Innovation, and Financing

In this section, as indicated by its name, the Parliament lists its statements on research, development, innovation, and financing in the context of the European hydrogen strategy.

First, the EU Parliament addresses the role of research, development, and innovation:

Stresses the importance of research, development and innovation along the whole value chain and of carrying out demonstration projects [. . .] including pilot projects [. . .] in making renewable hydrogen competitive and affordable.

Calls on the Commission to stimulate research and innovation efforts relating to the implementation of large-scale high-impact projects.

Underlines that significant amounts of money need to be invested to develop and increase the production capacity of renewable hydrogen [. . .] which would also require de-risking renewable hydrogen investments, for example through Contracts for Difference.

Calls on the Commission to develop a [. . .] renewable energy and hydrogen investment strategy aligned with national research and innovation strategies.

Welcomes the European Clean Hydrogen Alliance [and] *the important projects of common European interest (IPCEI) amongst other renewable hydrogen initiatives.* [Also] encourages the Alliance to come up, in cooperation with [. . .] FCH JU, with an investment agenda and a project pipeline.

Welcomes the renewal of the FCH JU under Horizon Europe; stresses the importance of its work and asks the Commission to use it as a competence centre for hydrogen and provide it with sufficient financial resources [. . .] [also] *calls on the Commission to make use of the experience gained through the FCH JU and to incentivise further research into fuel cell and hydrogen energy technologies.*

Believes that EU research and development efforts should focus on a wide range of potential new renewable hydrogen sources and technologies, such as hydrogen from photosynthesis, algae or electrolysers with sea water.

Concerning this subject, it is useful to refer to the Commission Staff Working Document building a European research area for clean hydrogen—the role of EU research and innovation investments to deliver on the EU's hydrogen strategy [38]—issued in January 2022.

In this document, the role of research, development, innovation, and funding is analysed, remarking its importance in maintaining Europe's technological leadership in renewable hydrogen, and many member states have embraced research and innovation in their own hydrogen strategies. The EU Research and Innovation Framework Programmes have enabled the investment of more than 1 billion euros through two FCH JU to develop hydrogen technologies and projects during the 2008–2021 period. However, there is still a need for investments in the research and innovation field, especially to give non-competitive but market-ready hydrogen technologies the means to be deployed and also to give an impulse to the associated advantages, such as new jobs creation in the EU (up to 5.4 million positions by 2050) and the increase in energy supply autonomy.

The development of a common Strategic Research and Innovation Agenda for renewable hydrogen is one goal of the European research area, although some of the necessary research and innovation activities can be already defined:

- Encompass large-scale demonstration projects.
- Cover new renewable hydrogen production technologies.
- Support every renewable energy technology and source since the production of renewable hydrogen requires renewable energy in large quantities and low prices.
- Encourage investments to develop projects with large-scale integrated hydrogen value chains.
- Stimulate the development of safe hydrogen infrastructure.
- Devise solutions for hard to abate transport sectors (aviation, train, heavy-duty vehicles, maritime).

Furthermore, regarding some cross-cutting issues:

- Encourage circularity of hydrogen equipment.
- Address the impact of hydrogen technology (environmentally, socially, economically).
- Reduce the consumption of critical raw materials.
- Enhance safety and public acceptance of the hydrogen technologies.

Another concept mentioned by the Parliament is Important Projects of Common European Interest (IPCEI), which is an instrument that will support hydrogen projects, particularly large-scale and cross-border projects that are beneficial for the European Union. In the Commission Staff Working Document previously mentioned, it is stated that 22 countries that belong to the European Union, as well as Norway, agreed to the establishment of IPCEIs in the hydrogen sector, having signed a manifesto in 2020, but it has not been adopted yet. It did, however, gain the interest of the industrial sector.

Furthermore, a project pipeline is being developed in Europe by the Clean Hydrogen Alliance, particularly regarding bankable investment projects that cover the entire hydrogen value chain, and one significant outcome is the easier coordination of investments between public and private stakeholders.

The Parliament also comments on the importance of FCH JU, which was mentioned throughout this review; therefore, it is time to properly break down this partnership.

The partnership Fuel Cells and Hydrogen Joint Undertaking is both private and public, and its objective is to support the research, development, and demonstration of hydrogen and fuel cell technologies in Europe. This partnership was established in May 2008 joining the European Commission, Hydrogen Europe (representing industries), and Hydrogen Europe Research, working from 2014 under Horizon 2020.

However, the present tense might not be adequate to use; the partnership had a second phase "FCH 2 JU" and finally terminated its functions in November 2021. Nevertheless, it was quickly followed by Clean Hydrogen JU (also Clean Hydrogen Partnership), established the day after to be the successor of FCH JU.

FCH JU has indeed played a crucial role in the hydrogen sector's development in Europe; it has enabled the collaboration of different stakeholders; it has participated in the deployment of 72 of the 159 hydrogen refuelling stations in Europe; it has also supported the hydrogen valleys and created the TRUST database; and much more.

In short, this partnership has and will continue to contribute to the development of hydrogen sector in Europe.

In this section the Parliament also:

> [Enumerates some EU] *financing instruments* [and] programmes [that] *have a key role* [in the] *development of a hydrogen economy across the EU,* [such as:] *the Recovery and Resilience Facility, Horizon Europe, the Connecting Europe Facility, InvestEU [. . .], the European Regional Development Fund, the Cohesion Fund, the Just Transition Fund and the ETS Innovation Fund*.

> [Also] *stresses the need to make sure there are synergies between [. . .] investment funds, programmes and financial instruments*.

Some of the funding instruments are relatively new, such as the Recovery and Resilience Facility, aiming to alleviate the impact of the coronavirus pandemic. Horizon Europe, for instance, focuses on research and innovation in different fields with 95.5 billion euros as a budget. Another example mentioned is the Cohesion Fund, which supports investment concerning member states with a GNI per capita below 90% EU-27 average, regarding transport infrastructure and environment.

Regarding the synergies, the Commission does indeed support synergies between the European funding instruments since they are key to uniting resources, which can lead to operational agreements. The Clean Hydrogen Joint Undertaking, for instance, may benefit from collaborating with other European partnerships, such as:

- 2ZERO;
- European Partnership on zero-emission waterborne transport;
- European Partnership for transforming Europe's rail system;
- European Partnership for Clean Aviation;
- Processes4Planet;
- European Partnership for Clean Steel;
- European Partnership for Clean Energy Transition.

The final topic discussed in this section is:

> *The inclusion of hydrogen deployment in the general objectives of the Partnership for Research and Innovation in the Mediterranean Area (PRIMA) [. . .] in order to strengthen research and innovation capacities and to develop [. . .] innovative solutions across the Mediterranean region*.

This partnership is actually focused on sustainable water management and agri-food systems in the Mediterranean region. It has been established since 2018 and ever since, it has developed tens of projects, but none of them emphasise hydrogen technologies.

While there are still no projects about hydrogen, the deployment of H_2 technologies can indirectly have an effect on the water management and agri-food sectors, such as the installation of desalination plants or the production of fertilisers with renewable hydrogen.

3.1.8. International Cooperation on Hydrogen

In this second-to-last section of the Parliament's Hydrogen Strategy, the subject discussed is Europe's international cooperation in the hydrogen sector.

> *It is emphasised that the EU's leading role in the production of hydrogen technologies presents an opportunity to promote EU industrial leadership and innovation on a global level while reinforcing the EU's role as a global climate leader; underlines [. . .] the goal of increasing domestic hydrogen production, while acknowledging that Member States may also [. . .] explore the possibility of importing energy or hydrogen*.

> *Moreover, the Parliament calls [. . .] on the Commission and the Member States to engage in an open and constructive dialogue in order to establish [. . .] cooperation*

and partnerships with neighbouring regions, such as North Africa, the Middle East and the Eastern Partnership countries [. . .] underlines that this cooperation would be beneficial for creating clean and new technology markets [. . .], enhancing the transition to renewable energy and achieving the UN Sustainable Development Goals

[Furthermore, the Parliament] emphasises international cooperation on hydrogen with non-EU countries, in particular with the UK, the European Economic Area, the Energy Community and the US [. . .] in order to strengthen the internal market and energy security; stresses that cooperation should be avoided with non-EU countries that are subject to EU restrictive measures [. . .] and with those that do not guarantee compliance with safety, environmental standards and transparency requirements.

[Finally,] *considers that hydrogen should become an element of the EU's international cooperation, inter alia within the framework of the International Renewable Energy Agency's (IRENA's) work [. . .] and the European Neighbourhood Policy*.

International cooperation is indeed of major significance to boost the green transition worldwide and, particularly, to enhance the hydrogen economy in Europe not only in relation to H_2 production but also for imports.

The Parliament remarks on some of the benefits of creating international partnerships, which is fitting given that the Commission is concentrating on multi-lateral collaborations with industrial countries and emerging economies. The Commission is also supporting cooperation with countries in close proximity to the EU and also Africa, Latin America, and potentially, some Eastern countries.

One example of international cooperation in the hydrogen sector is the Mission Innovation Clean Hydrogen Mission, which was established in June 2021 and was directed by the Commission, the UK, the US, Chile, and Australia. One main target is the development of at least a hundred large-scale, integrated, clean hydrogen valleys.

Another example is the participation of the Commission (and FCH JU) in organisations such as the Clean Energy Ministerial Hydrogen Initiative, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), and EUREKA.

Finally, it can be remarked that the Commission also works with the IRENA, the World Energy Council or IEA, and particularly, the IEA Hydrogen Technology Collaboration Programme in energy related matters and, specifically, hydrogen.

The Parliament also shows interest in making Europe the model, the reference point in terms of hydrogen, stating that:

The EU should promote its hydrogen standards and sustainability criteria internationally; [the Parliament also] *calls [. . .] for the development of international standards and the setting up of common definitions and methodologies for defining overall emissions from each unit of hydrogen produced, as well as international sustainability criteria as a prerequisite for [. . .] imports*.

[Moreover,] *encourages the Commission to promote the role of the euro as the reference currency in the international trade of hydrogen*.

This position is reasonable, especially when aiming to become the global hydrogen leader. However, some sources such as the German Energy Agency (dena) and World Energy Council—Germany in their report, Global Harmonisation of Hydrogen Certification, do not have such an optimistic impression. In this report, the feasibility of implementing a uniform global certification system for renewable H_2 is analysed. Certain standards and criteria from different countries and organisations are studied, and the conclusions express the complexity of reaching uniformity. Moreover, it is also noted that in that scenario of homogeneity of standards, the EU would have to give up some of its requirements regarding renewable hydrogen. This thought leads to the notion that within the current standardisation heterogeneity, the strict (stricter, when compared with other countries) requisites may result in a loss of appeal for the EU hydrogen market since companies would choose less rigid conditions in other markets.

3.1.9. The Role of Hydrogen in an Integrated Energy System

In this last section, the subject is the discussion on how hydrogen fits in an integrated energy system.

First, the EU Parliament:

> *Underlines the need for an integrated energy system in order to achieve climate neutrality by 2050 [. . .] and reach the goals of the Paris Agreement; welcomes in that regard the inclusion of hydrogen in the Commission's Strategy for Energy System Integration [. . .] considers that more emphasis needs to be placed on innovative projects combining the production and recovery of electricity, hydrogen and heat*.

This EU Strategy for Energy System Integration was released by the Commission in July 2020 within the Green Deal and counts on the implementation of the Clean Energy Package that was analysed in a previous section.

An integrated energy system translates as the interconnection of different energy carriers and energy end uses with themselves and each other [39] Therefore, electricity, heat and cold, and fuels can be linked to each other; industry, transport and buildings can also be linked to each other; and they can all join and be an integrated system. This can ease decarbonisation and optimise the energy system.

In relation to hydrogen in the strategy, its capacity to store energy from renewable sources and its buffering ability are remarked on and so are its possible applications in heavy-duty road transport, rail transport, industrial processes, and its use as synthetic fuel in maritime transport and aviation.

Finally, the Parliament:

> *Notes that the development of the hydrogen economy can contribute to reducing imbalances in the energy system [. . .] [since] hydrogen can play a key role in terms of storing energy to compensate for fluctuations in renewable energy supply and demand*.
>
> *Highlights that an ambitious and timely strategy for energy storage through the use of hydrogen is required; notes, however, that the use of hydrogen for energy storage is not competitive yet*.
>
> *Underlines [. . .] the need to bring down costs for renewable hydrogen production [. . .] therefore encourages the Commission to analyse options and capacities for hydrogen storage*.

The Commission is indeed taking an interest in analysing hydrogen storage, as proven by the report issued in February 2022. The role of renewable H_2 import and storage is to scale up the EU deployment of renewable H_2 [40] by the Energy Transition Expertise Centre.

Some of the benefits of the deployment of hydrogen storage are recognised, such as:

- Security of supply, since having hydrogen stored allows for its use whenever needed.
- Enabling system flexibility; the H_2 storage can help maintain the stability of the network, can serve as a buffer in response to supply and demand variations, and can help to meet extreme or peak demands.
- Optimal development of infrastructure.

Furthermore, for individual actors:

- For electrolyser operators, storage enables the decoupling of production and consumption times.
- For H_2 consumers, the stability provided by storage can prevent price fluctuations, and can also contribute to the deployment of end uses affected by variations of demand.

Finally, although better detailed and explained in the correspondent document, Figure 8 shows some of the barriers and measures to confront them that were analysed in the report.

BARRIERS FOR H_2 STORAGE DEVELOPMENT	MEASURES TO ADDRESS THESE BARRIERS
Hydrogen markets will develop slowly	Integrated planning of the hydrogen, gas and electricity systems
Energy sector planning may not consider storage characteristics	
The need for regulation of storage will vary across Member States and storage types	A clear, predictable regulatory framework for large-scale hydrogen storage
There is regulatory uncertainty concerning the conversion of currently regulated gas storages	
Market design and network tariffs may not reward the benefits of hydrogen storage	Development of hydrogen markets design and network tariff structures to value H_2 storage properly

Figure 8. Barriers and measures regarding hydrogen storage [40].

From here on, the EU organisations and other involved actors need to carefully keep developing the hydrogen storage sector and market.

3.2. Precedents

Given the Commission's role of proposing and designing strategies, it is no surprise to learn that there already is a European strategy for hydrogen, particularly a hydrogen strategy for a climate-neutral Europe, developed by the Commission and issued in July 2020.

The documents considered are similar in theme; after all, they are both European strategies for hydrogen. As seen in Figure 9, they have different structures but touch on many of the same topics.

One remarkable aspect is that in the first document, the Commission is explaining certain circumstances regarding hydrogen and what they are doing or will be doing about them. The Parliament's piece, however, is a constant appeal to the Commission and sometimes also to the member states, calling on them to attend to several requests, as was made evident in the previous section.

In terms of content, as mentioned before, there are clear similarities that can be seen just by reading the section names; for example, the Commission's "Boosting demand and scaling up production" shares similarities with the Parliament's "Ramping up hydrogen production" and "Hydrogen demand", and so do the Commission's "The international dimension" and the Parliament's "International cooperation on hydrogen", among other sections.

Furthermore, the Parliament's strategy was released almost a year after the Commission's, and therefore, the Parliament uses the latter as reference. That is why it is not rare to find the Parliament "welcoming" some of the Commission's proposals or ambitions.

Another instance is the direct reference to the Commission's hydrogen classification, which appears in its strategy, pointing out the double use of renewable and clean for the same category of hydrogen but welcoming it as a first step.

Regarding the differences between the content of the strategies, it can be affirmed that the Commission's document is more thorough about the subjects it analyses, and even though it was issued previous to the Parliament's document, it covers some aspects that the former does not.

For instance, the Commission presents an investment agenda, giving estimations of the investments required for electrolysers (EUR 24–42 billion), renewable energy production (EUR 220–340 billion), retrofitting half of the CCS/U plants (EUR 11 billion), and HRS, transport, distribution, and storage of H_2 (EUR 65 billion).

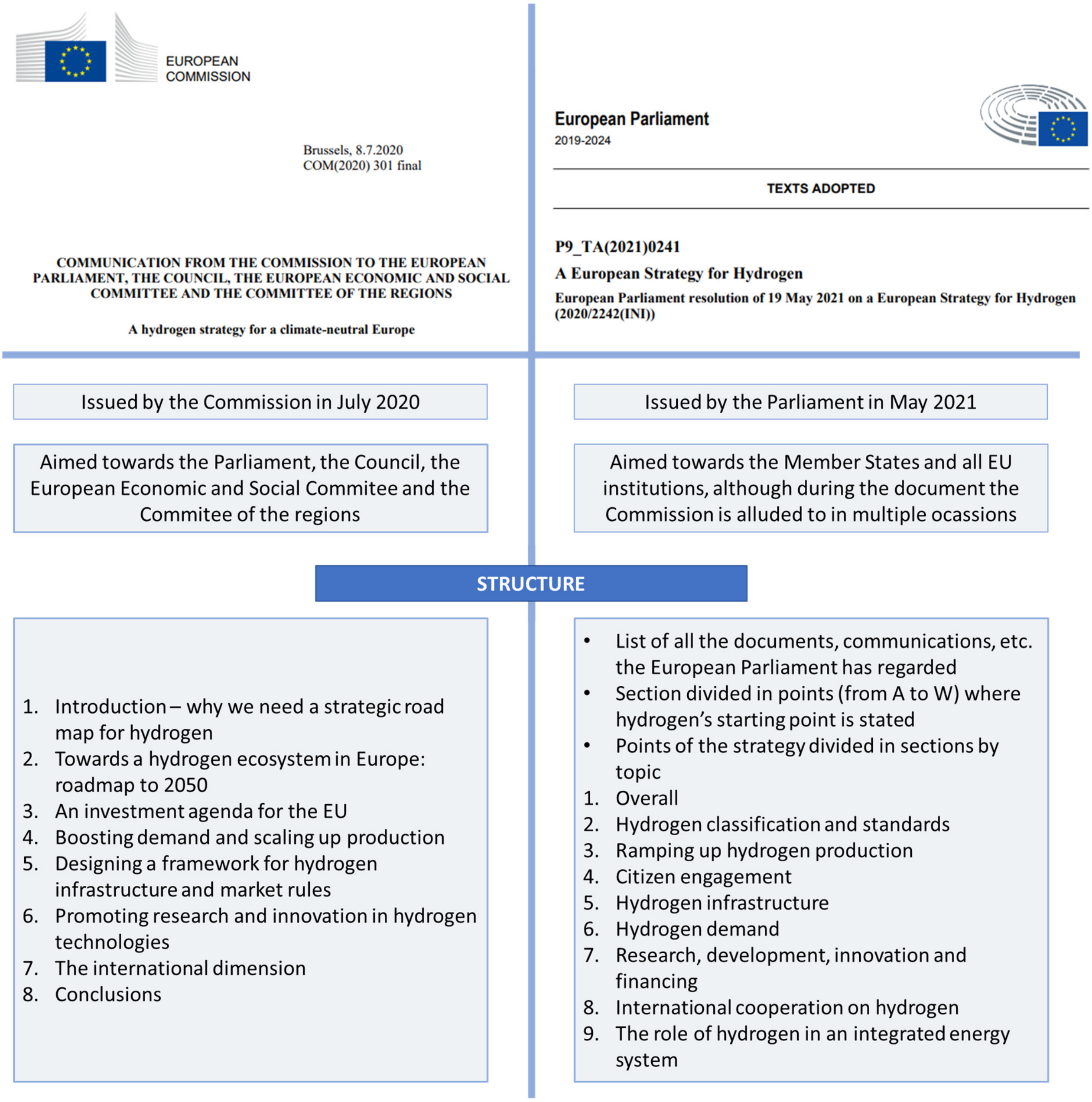

Figure 9. Schematic comparison of the two European hydrogen strategies [8].

The Parliament does remark on the importance of having an investment agenda but does not acknowledge the one now summarised.

Another aspect that the Parliament does not really acknowledge is the development of the hydrogen economy through the phases that the Commission defines. These phases express the renewable hydrogen electrolyser capacity for the coming years, as well as the development of infrastructure and applications.

Finally, it is interesting to list some of the documentation that was released in between the two strategies:

- The European Parliament's resolution on a comprehensive European approach to energy storage (10 July 2020).
- The European Parliament's resolution on the revision of the guidelines for trans-European energy infrastructure (10 July 2020).

- The European Commission's communication "Stepping up Europe's 2030 climate ambition—Investing in a climate-neutral future for the benefit of our people" (17 September 2020).
- The European Commission's report "2020 report on the State of the Energy Union pursuant to Regulation (EU) 2018/1999 on Governance of the Energy Union and Climate Action" (14 October 2020).
- The European Commission's communication on an EU strategy to reduce methane emissions (14 October 2020).
- The European Commission's Pact for Skills (10 November 2020).
- The European Commission's communication on an EU strategy to harness the potential of offshore renewable energy (19 November 2020).
- The UN Environment Programme's Emissions Gap Report 2020 (9 December 2020).
- The European Commission's communication "Sustainable and Smart Mobility Strategy—putting European transport on track for the future" (9 December 2020).
- IRENA's report "Green hydrogen cost reduction—scaling up electrolysers to meet the 1.5 °C climate goal" (December 2020).
- The European Commission's adoption of the proposal to revise the regulation on trans-European networks in energy (TEN-E) (15 December 2020).
- The European Commission's communication "Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery" (5 May 2021).

Given all the reports, communications, and resolutions issued from strategy to strategy, one can only imagine what changes will be implemented in the next hydrogen strategy type of document, especially after the scale up of the conflict with Russia, which has and will continue to affect the energy market and, therefore, the hydrogen economy development.

4. Conclusions and Policy Implications

This work has allowed for an overview and analysis of the European Union's position within the hydrogen sector.

Concerning the Parliament's hydrogen strategy, it is appropriate to express its importance since it is the document that gives the reader an understanding of how the EU intends to function in the hydrogen sector. Moreover, in the analysis elaborated, its effects can be recognised in terms of projects developed or policies adopted.

It is also remarkable that in just a few pages, the European Parliament manages to cover a wide range of topics, all of them significant to represent the entirety of the hydrogen sector. It touches on subjects such as H_2 demand, infrastructure, research, standards, etc., enabling a complete approach to the sector.

Another aspect that the strategy mentions is the intention of the EU to be a leader in the hydrogen sector, and this purpose is corroborated by the large number of associations, strategies, plans, and projects that are being established and developed by the European Union and have come up throughout this review.

However, the supply of critical raw materials (CRMs) is an important aspect that needs to be covered further, and dedicated policies need to be addressed [41]. IEA states that the technologies for the energy transition require a significant increase in the use of CRM [42], and hydrogen technologies are demanding important amounts of CRMs, such as PGMs (platinum group metals), including not only platinum [43] but also other electrocatalysts such as iridium.

Furthermore, it will be interesting to see how the EU updates its hydrogen strategy given the current context of energy prices inflation and the conflict with Russia. As an example, during 2022, the plans to expand the natural gas grid capabilities to transport and distribute hydrogen within Europe, including Eastern countries, were clearly accelerated, with announcements of further extension in terms of both km of pipelines and investments.

Finally, the most important conclusions to learn from this study are that hydrogen has many of the right characteristics to make it the key to decarbonisation, especially in hard-to-abate sectors, and that it is bound to be one of the main actors in the imminent green transition. Moreover, hydrogen seems to be having its breakthrough, particularly in Europe, and this field's development can have benefits not only from an environmental perspective but also from an economical one, where the EU intends to lead the way into the green transition and the fight against climate change according to the statements discussed and published in its hydrogen strategy.

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Abbreviations

CCS/U	Carbon capture storage and utilisation
CHP	Combined heat and power
CO_2	Carbon dioxide
CRM	Critical raw material
DOE	Department Of Energy (US Department of Energy)
EEA	European economic area
EU	European Union
EUR	Euro
FC	Fuel cell
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
GNI	Gross national income
GO	Guarantee of origin
HRS	Hydrogen refuelling station
H_2	Hydrogen
IEA	International Energy Agency
LWH	Lower heating value
LNG	Liquid/liquefied natural gas
LPG	Liquefied petroleum fas
MJ	Megajoule
NH_3	Ammonia
PEM	Polymer electrolyte membrane
PGM	Platinum group metal
PV	Photovoltaic
RES	Renewable energy source
SME	Small- and medium-sized enterprise
SOFC	Solid oxide fuel cell
TJ	Terajoule
UK	United Kingdom
UN	United Nations
US	United States
USD	United States dollar

References

1. Hassan, Q.; Abdulateef, A.M.; Hafedh, S.A.; Al-samari, A.; Abdulateef, J.; Sameen, A.Z.; Jaszczur, M. Renewable energy-to-green hydrogen: A review of main resources routes, processes and evaluation. *Int. J. Hydrogen Energy*, **2023**, *in press*.
2. Falcone, P.M.; Hiete, M.; Sapio, A. Hydrogen economy and sustainable development goals: Review and policy insights. *Curr. Opin. Green Sustain. Chem.* **2021**, *31*, 100506. [CrossRef]

3. Nazir, H.; Louis, C.; Jose, S.; Prakash, J.; Muthuswamy, N.; Buan, M.E.; Flox, C.; Chavan, S.; Shi, X.; Kauranen, P.; et al. Is the H2 economy realizable in the foreseeable future? Part I: H2 production methods. *Int. J. Hydrogen Energy* **2020**, *45*, 13777–13788. [CrossRef]
4. Younas, M.; Shafique, S.; Hafeez, A.; Javed, F.; Rehman, F. An Overview of Hydrogen Production: Current Status, Potential, and Challenges. *Fuel* **2022**, *316*, 123317, ISSN 0016-2361. [CrossRef]
5. Nazir, H.; Muthuswamy, N.; Louis, C.; Jose, S.; Prakash, J.; Buan, M.E.; Flox, C.; Chavan, S.; Shi, X.; Kauranen, P.; et al. Is the H2 economy realizable in the foreseeable future? Part II: H2 storage, transportation, and distribution. *Int. J. Hydrogen Energy* **2020**, *45*, 20693–20708. [CrossRef]
6. Langmi, H.W.; Engelbrecht, N.; Modisha, P.M.; Bessarabov, D. Chapter 13—Hydrogen Storage. In *Electrochemical Power Sources: Fundamentals, Systems, and Applications*; Smolinka, T., Garche, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 455–486. ISBN 9780128194249.
7. Nazir, H.; Muthuswamy, N.; Louis, C.; Jose, S.; Prakash, J.; Buan, M.E.; Flox, C.; Chavan, S.; Shi, X.; Kauranen, P.; et al. Is the H2 economy realizable in the foreseeable future? Part III: H2 usage technologies, applications, and challenges and opportunities. *Int. J. Hydrogen Energy* **2020**, *45*, 28217–28239. [CrossRef] [PubMed]
8. European Parliament. TA-9-2021-0241_EN: European Parliament Resolution of 19 May 2021 on a European Strategy for Hydrogen. Available online: https://www.europarl.europa.eu/doceo/document/TA-9-2021-0241_EN.html (accessed on 15 February 2022).
9. United Nations Framework Convention on Climate Change. Key Aspects of the Paris Agreement. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement#:~:text=The%20Paris%20Agreement%27s%20central%20aim,further%20to%201.5%20degrees%20Celsius (accessed on 19 May 2022).
10. International Energy Agency. Data and Statistics. Available online: https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy%20consumption&indicator=TFCbySource (accessed on 19 May 2022).
11. International Energy Agency. Data and Statistics. Available online: https://www.iea.org/data-and-statistics/data-browser/?country=WEOEUR&fuel=Energy%20consumption&indicator=TFCbySource (accessed on 19 May 2022).
12. International Energy Agency. Data and Statistics. Available online: https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=CO2%20emissions&indicator=CO2BySector (accessed on 19 May 2022).
13. International Energy Agency. Data and Statistics. Available online: https://www.iea.org/data-and-statistics/data-browser/?country=WEOEUR&fuel=CO2%20emissions&indicator=CO2BySector (accessed on 19 May 2022).
14. European Commission. Home:Strategy:Priorities 2019–2024: A European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 7 June 2022).
15. European Commission. Home: Strategy:Priorities 2019–2024: A European Green Deal: Delivering the European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en (accessed on 7 June 2022).
16. European Commission. Home:Strategy:Priorities 2019–2024: A European Green Deal: REPowerEU: Affordable, Secure and Sustainable Energy for Europe. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en (accessed on 18 June 2022).
17. European Commission. REPowerEU: Joint European Action for More Affordable, Secure and Sustainable Energy. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_1511 (accessed on 19 May 2022).
18. United Nations. Department of Economic and Social Affairs, Sustainable Development, Sustainable Development Goals. Available online: https://sdgs.un.org/goals (accessed on 18 June 2022).
19. European Commission. European Industrial Strategy. Available online: https://ec.europa.eu/growth/industry/strategy_en (accessed on 7 June 2022).
20. Buttler, A.; Spliethoff, H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2440–2454. [CrossRef]
21. International Renewable Energy Agency. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 °C Climate Goal*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2020.
22. European Clean Hydrogen Alliance. European Electrolyser Summit: Joint Declaration. Available online: https://hydrogeneurope.eu/wp-content/uploads/2022/05/2022.05.05-EU-ELY-Summit_joint-declaration_signed-c70ff98b5001f55b76b50cf0221c895f.pdf (accessed on 7 June 2022).
23. Fuel Cells and Hydrogen Joint Undertaking. Mission Innovation Hydrogen Valley Platform. Available online: https://www.h2v.eu/ (accessed on 7 June 2022).
24. Fuel Cells and Hydrogen Joint Undertaking. Hydrogen Valleys: Insights into the Emerging Hydrogen Economies Around the World. Available online: https://www.fch.europa.eu/sites/default/files/documents/20210527_Hydrogen_Valleys_final_ONLINE.pdf (accessed on 18 June 2022).
25. Fuel Cells and Hydrogen Joint Undertaking. Mission Innovation Hydrogen Valley Platform: HyWays for Future. Available online: https://www.h2v.eu/analysis/best-practices/hyways-future (accessed on 18 June 2022).
26. HyNet North West. About: What Is HYNET? Available online: https://hynet.co.uk/about/ (accessed on 18 June 2022).
27. Hydrogenious. Applications for a "Hydrogenated" World. Available online: https://www.hydrogenious.net/index.php/en/references/blue_danube/ (accessed on 7 June 2022).

28. European Commission. A Hydrogen Strategy for a Climate-Neutral Europe. Available online: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (accessed on 7 June 2022).
29. CertifHy. About Us: Our Mission and Vision. Available online: https://www.certifhy.eu/ (accessed on 18 June 2022).
30. Babaei, R.; Ting, D.S.; Carriveau, R. Optimization of hydrogen-producing sustainable island microgrids. *Int. J. Hydrogen Energy* **2022**, *47*, 14375–14392. [CrossRef]
31. European Environment Agency. *Water Resources Across Europe—Confronting Water Stress: An Updated Assessment*; Report; European Environment Agency: Copenhagen, Denmark, 2021.
32. Böhm, H.; Moser, S.; Puschnigg, S.; Zauner, A. Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials. *Int. J. Hydrogen Energy* **2021**, *46*, 31938–31951.
33. Schlund, D.; Schönfisch, M. Analysing the impact of a renewable hydrogen quota on the European electricity and natural gas markets. *Appl. Energy* **2021**, *304*, 117666, ISSN 0306-2619. [CrossRef]
34. Toktarova, A.; Göransson, L.; Johnsson, F. Design of Clean Steel Production with Hydrogen: Impact of Electricity System Composition. *Energies* **2021**, *14*, 8349. [CrossRef]
35. European Commission. Mobility and Transport: Trans-European Transport Network (TEN-T). Available online: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en (accessed on 7 June 2022).
36. European Commission. Questions and Answers: The Revision of the TEN-T Regulation. Available online: https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_6725 (accessed on 7 June 2022).
37. European Parliament. Briefing: Revision of the Trans-European Transport Network Guidelines. Available online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/729314/EPRS_BRI(2022)729314_EN.pdf (accessed on 18 June 2022).
38. European Commission. Commission Staff Working Document: Building a European Research Area for Clean Hydrogen—The Role of EU Research and Innovation Investments to Deliver on the EU's Hydrogen Strategy. Available online: https://ec.europa.eu/info/sites/default/files/research_and_innovation/research_by_area/documents/ec_rtd_swd-era-clean-hydrogen.pdf (accessed on 18 June 2022).
39. European Commission. EU Strategy on Energy System Integration. Available online: https://energy.ec.europa.eu/topics/energy-system-integration/eu-strategy-energy-system-integration_en (accessed on 18 June 2022).
40. Energy Transition Expertise Centre. Report: The Role of Renewable H_2 Import & Storage to Scale Up the EU Deployment of Renewable H2. Available online: https://op.europa.eu/en/publication-detail/-/publication/7ab70e32-a5a0-11ec-83e1-01aa75ed71a1/language-en (accessed on 18 June 2022).
41. European Commission. *Study on the EU's List of Critical Raw Materials*; Final Report; Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Joint Research Centre Directorate GROW.C, JRC.D: Brussels, Belgium, 2020; ISBN 978-92-76-21049-8.
42. International Energy Agency. *World Energy Outlook 2022*; IEA Publications: Paris, France, 2022.
43. Lotrič, A.; Sekavčnik, M.; Kuštrin, I.; Mori, M. Life-cycle assessment of hydrogen technologies ith the focus on EU critical raw materials and end-of-life strategies. *Int. J. Hydrogen Energy* **2021**, *46*, 10143–10160. [CrossRef]