UNIVERSITY OF PIRAEUS
Department of International & European Studies
MSc in Energy: Strategy, Law and Economics

Master Thesis

# Hydrogen economy

# Legislative framework & current status

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(υπογραφή)

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I would like to dedicate this dissertation to my husband and kids for the patience and support they have shown over the last year and a half. Without their help and patronage this dream would never come true.

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## List of Abbreviations

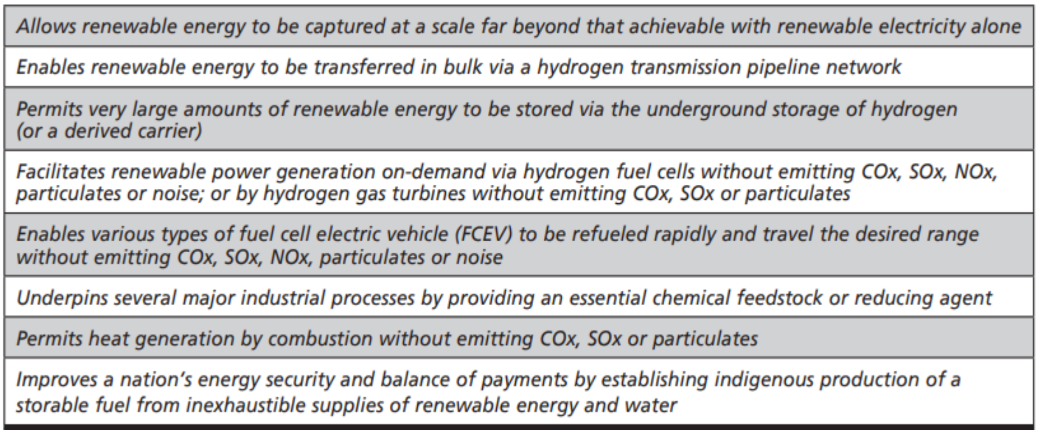
| | |
|---|---|
| **EU** | European Union |
| **GHG** | Greenhouse gas |
| **GOs** | Guarantees of Origin |
| **CO2** | Carbon Dioxide |
| **NOX** | Nitrous oxide |
| **EC** | European Commission |
| **SMR** | Steam methane reforming |
| **ATR** | Autothermal reforming |
| **POX** | Partial oxidation |
| **CCS** | Carbon capture and storage |
| **EOR** | Enhanced oil recovery |
| **IMF** | International Monetary Fund |
| **EASAC** | European Academies Science Advisory Council |
| **MEAs** | Membrane-electrode assemblies |
| **BOP** | Balance of plant |
| **HHV** | Higher heating value |
| **PEM** | Proton exchange membrane |
| **R&D** | Research and development |
| **TFEU** | Treaty on the Functioning of the European Union |
| **CE** | European Conformity |
| **PED** | Pressure Equipment Directive |
| **AFID** | Alternative fuels infrastructure directive |
| **CNG** | Gaseous natural gas |
| **LNG** | Liquefied natural gas |

| | |
|---|---|
| **LPG** | Liquefied petroleum gas |
| **RED** | Renewable energy directive |
| **ETS** | Emission trading system |
| **IPCEI** | Important Projects of Common European Interest |
| **CHP** | Combined heat and power |
| **FCEV** | Fuel cell electric vehicle |

# CHAPTER 1: INTRODUCTION

In 1874, science fiction author Jules Verne set out a prescient vision that has inspired governments and entrepreneurs in the 147 years since. In his book «The Mysterious Island», Verne wrote of a world where “…water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable…”. We are close to this point in 2021, as both in Europe and in the rest of the developed world, intensive efforts are being made to consolidate the "hydrogen economy" with significant funds being invested in research and development in this direction.

Hydrogen is the most abundant element in the universe, but it does not occur naturally on Earth. Energy is required to extract it from fossil fuels, biomass or water, with water being the most plentiful source. Energy is also required to manufacture the technologies involved in hydrogen production, purification, storage and utilization. Therefore, a set of compelling reasons is needed to justify switching to hydrogen in our efforts to decarbonize the energy system and reduce atmospheric pollution [Table 1]:



| |
|---|
| *Allows renewable energy to be captured at a scale far beyond that achievable with renewable electricity alone* |
| *Enables renewable energy to be transferred in bulk via a hydrogen transmission pipeline network* |
| *Permits very large amounts of renewable energy to be stored via the underground storage of hydrogen (or a derived carrier)* |
| *Facilitates renewable power generation on-demand via hydrogen fuel cells without emitting COx, SOx, NOx, particulates or noise; or by hydrogen gas turbines without emitting COx, SOx or particulates* |
| *Enables various types of fuel cell electric vehicle (FCEV) to be refueled rapidly and travel the desired range without emitting COx, SOx, NOx, particulates or noise* |
| *Underpins several major industrial processes by providing an essential chemical feedstock or reducing agent* |
| *Permits heat generation by combustion without emitting COx, SOx or particulates* |
| *Improves a nation’s energy security and balance of payments by establishing indigenous production of a storable fuel from inexhaustible supplies of renewable energy and water* |

**Table 1. The fundamental reasons for adopting hydrogen in the energy system.**

Hydrogen is very useful for carrying, storing and utilizing renewable energy as and when required by various types of end use. To achieve a climate-neutral energy system by 2050, it is important to ensure ‘net zero’ hydrogen is produced, and that hydrogen supply and demand are well matched throughout the transition. Consideration should therefore be given to the ultimate capacity of each hydrogen production method, its ability to facilitate a progression in supply and demand, and the greenhouse gas (GHG) footprint of the hydrogen it produces [1].

Hydrogen can be used as a feedstock, a fuel or an energy carrier and storage, and has many possible applications across industry, transport, power and buildings sectors. Most importantly, it does not emit CO2 and does not pollute the air when used.

It can help to decarbonize industrial processes and economic sectors where reducing carbon emissions is both urgent and hard to achieve. Today, the amount of hydrogen used remains limited, and it is largely produced from fossil fuels. Ultimate goal today, is to decarbonize hydrogen production - made possible by the rapid decline in the cost of renewable energy and acceleration of technology developments - and to expand its use in sectors where it can replace fossil fuels [2].

## 1.1 Hydrogen properties

Hydrogen is a colorless, odorless, tasteless, and nonpoisonous gas under normal conditions on Earth. It typically exists as a diatomic molecule, meaning each molecule has two atoms of hydrogen. This is why pure hydrogen is commonly expressed as “H2“.

Hydrogen is the most abundant element in the universe, accounting for 90 percent of the universe by weight. However, it is not commonly found in its pure form since it readily combines with other elements. It is also the lightest element, having a density of 0.08988 grams per liter at standard pressure.

Hydrogen has several important chemical properties that affect its use as a fuel:

- It combines with oxygen to form water, which is absolutely necessary for life on this planet.

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[1] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

[2] European Commission, «Questions and answers: A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

- It has a high energy content per weight (nearly 3 times as much as gasoline), but the energy density per volume is quite low at standard temperature and pressure. Volumetric energy density can be increased by storing the hydrogen under increased pressure or storing it at extremely low temperatures as a liquid. Hydrogen can also be adsorbed into metal hydrides.
- Hydrogen is highly flammable; it only takes a small amount of energy to ignite it and make it burn. It also has a wide flammability range, meaning it can burn when it makes up 4 to 74 percent of the air by volume.
- Hydrogen burns with a pale blue, almost-invisible flame, making hydrogen fires difficult to see.
- The combustion of hydrogen does not produce carbon dioxide (CO2), particulate, or sulfur emissions. It can produce nitrous oxide (NOX) emissions under some conditions.
- Hydrogen can be produced from renewable resources, such as by reforming ethanol (this process emits some carbon dioxide) and by the electrolysis of water (electrolysis is very expensive).

H2 as a fuel has a high specific energy per unit mass of 120MJ / kg and a small specific energy per unit volume of 8 MJ / L (Figure 1). Figure 1 shows the comparison in terms of gravimetric and volumetric density. It is evident that larger volumes are necessary for H2 storage, due to its low volumetric energy content, leading to higher costs. By burning it, that is, by combining it with oxygen, water and heat are produced.

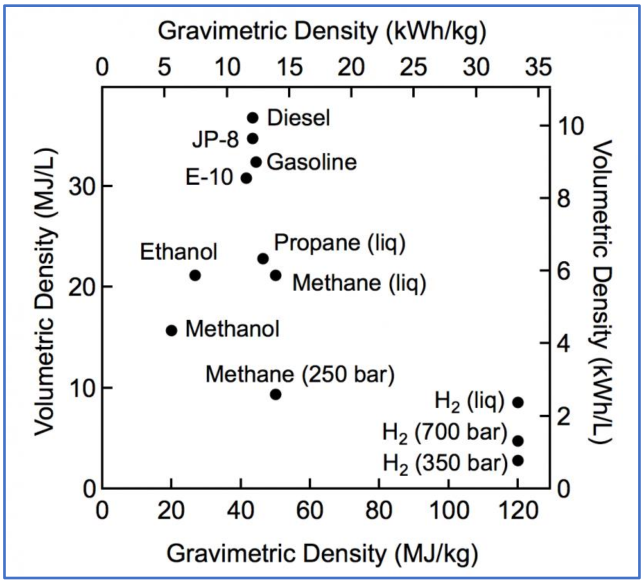

*Figure 1. Gravimetric and volumetric density of hydrogen and other fuels*

## 1.2 Hydrogen uses/applications [3]

Hydrogen is a key solution to cut greenhouse gas emissions in sectors that are hard to decarbonize and where electrification is difficult or impossible. This is the case of industrial sectors such as steel production, or heavy-duty transport for example. As a carbon-free energy carrier, hydrogen would also allow for transport of renewable energy over long distances and for storage of large energy volumes.

An immediate application in industry is to reduce and replace the use of carbon-intensive hydrogen in refineries, the production of ammonia, and for new forms of methanol production, or to partially replace fossil fuels in steel making. Hydrogen holds the potential to form the basis for zero-carbon steel making processes in the EU, envisioned under the Commission's New Industrial Strategy.

In transport, hydrogen is also a promising option where electrification is more difficult. For example, in local city buses, commercial fleets or specific parts of the rail network. Heavy-duty vehicles including coaches, special purpose vehicles, and long-haul road freight could also be decarbonized by using hydrogen as a fuel. Hydrogen fuel-cell trains could be extended, and hydrogen could be used as a fuel for maritime transport on inland waterways and short-sea shipping.

In the long term, hydrogen can also become an option to decarbonize the aviation and maritime sector, through the production of liquid synthetic kerosene or other synthetic fuels.

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[3] European Commission, «Questions and answers: A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

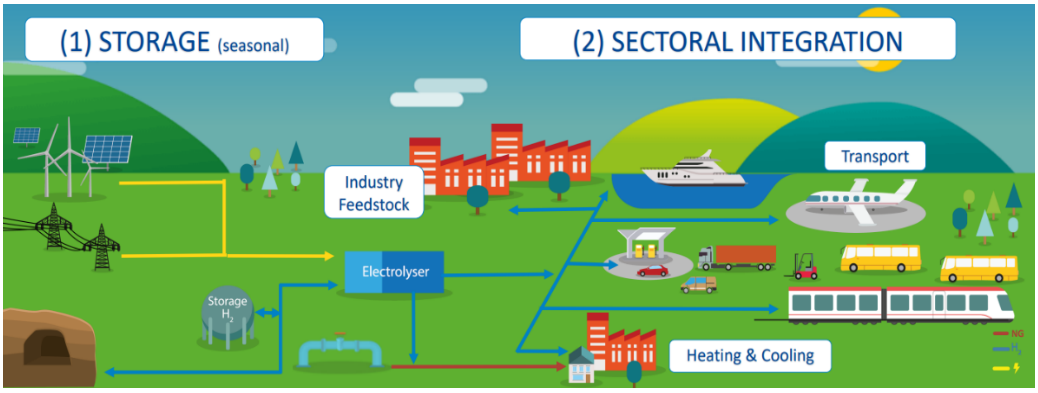

*Figure 2. The role of hydrogen in our society & economy*[4]

## 1.3 Hydrogen advantages and disadvantages

The advantages of H2 as an energy carrier can be summarized as follows:

- It can be easily produced by different ways. The old way was from hydrocarbons, while today we are focused on its production from water.
- It is a very useful chemical element that is used either as a chemical reactant in chemical production processes or as a fuel.
- It can be stored in different forms and in large quantities (while electricity cannot be stored in large quantities).
- It can be transported either by means of transport over long distances or by pipeline networks and in fact with much smaller losses than those of the electricity transmission networks.
- It is environmentally friendly. The utilization of H2 involves a stage of oxidation during its combustion, where its product is water. A small amount of nitrogen oxides produced when H2 is ignited in air can be controlled by a more precise design of its combustion engines (Wallace and Ward 1983). The environmental burden from other phases of the H2 cycle, such as its production phase, is not always environmentally friendly and depends on the production method used.

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[4] European Hydrogen week, 23-27 November 2020, Fuel cells & hydrogen joint undertaking, Sharing best practices of green hydrogen projects in Europe, Bart Biebuyck, 16/09/2020, WebEx

The production of H2 e.g., from the reforming of hydrocarbons produces carbon dioxide (CO2).

- It is a recyclable energy carrier. It oxidizes to water and water can be redistributed into hydrogen and oxygen.

H2 has some other features that are disadvantages:

- Its energy density is lower than that of gasoline and diesel. The highest energy density of H2 can be achieved in the liquid phase and reaches 80% of the corresponding gasoline (on a mass basis). Based on the volume, its highest energy density is achieved with metal hydrides and reaches 35% of the corresponding gasoline.
- It is very easy to leak from its storage tanks due to its density and low specific gravity.
- The cost of its production, apart from that of the reforming of hydrocarbons, remains high.

## 1.4 Hydrogen hazards [5]

Hydrogen is a highly flammable gas and care must be taken that hydrogen is produced, stored, transported and utilised in a safe manner. Standards are already in place, and the European industry has built up significant experience with already more than 1500 km of dedicated hydrogen pipelines in place. With hydrogen consumption expanding to other markets and end-use applications, the strategy points out that the need for safety standards from production, transport and storage to use is critical, include a system to monitor and verify.

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[5] European Commission, «Questions and answers: A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

# CHAPTER 2: HYDROGEN TYPES/COLOUR CODES

Hydrogen itself is a colourless gas but there are around nine colour codes to identify hydrogen. The colour codes of hydrogen refer to the source or the process used to make hydrogen. These codes are green, blue, grey, brown or black, turquoise, purple, pink, red and white.

*Figure 3. Hydrogen colour codes*

## 2.1 Black/brown hydrogen [6]

Black or brown hydrogen is produced from coal. The black and brown colours refer to the type bituminous (black) and lignite (brown) coal. The gasification of coal is a method used to produce hydrogen. However, it is a very polluting process, and CO2 and carbon monoxide are produced as by-products and released to the atmosphere.

## 2.2 Grey hydrogen [7]

'Grey' hydrogen is produced commercially in large quantities from fossil fuels by a hydrocarbon reformation technique involving steam and/or oxygen, namely steam methane reforming (SMR) or autothermal reforming (ATR) of natural gas, and by partial oxidation (POX) of coal or heavy oil. In each case a mixture of hydrogen and

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[6] Hydrogen colours codes - H2 Bulletin

[7] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

carbon monoxide is produced (syngas), which then requires the carbon monoxide to be removed via the water-gas shift reaction to yield further hydrogen and carbon dioxide:

$$CO + H2O \rightarrow CO2 + H2$$

In total about 6% of global natural gas production and 2% of global coal production is used to make approximately 70 Mt of hydrogen per annum, and this results in atmospheric emissions of about 830 Mt of carbon dioxide.

Most of the existing hydrogen production is by steam methane reforming, because the required plant is of relatively low capital cost and the chemical reaction is easy to control. Reformer capacities lie mainly in the range of 50–1000 MW, they usually operate under steady-state conditions, and globally the current installed capacity is in the region of 300 GW.

The production of grey hydrogen at scale is long established and its further expansion is not capacity limited, although fossil fuel reserves are ultimately finite. The CO2 by-product is usually vented to atmosphere along with the CO2 emissions from the steam raising and oxygen production processes. Grey hydrogen production therefore makes a significant contribution to global warming.

It has been proposed to capture CO2 from the water-gas shift stage of SMR/ATR/POX and sequester it via carbon capture and storage (CCS) to reduce the GHG footprint of grey hydrogen, and so earn the prefix ‘blue’ or ‘low-carbon’. Capturing CO2 from the heat generation, steam raising, and oxygen production processes is also desirable in order to minimize the GHG footprint, but this is technically more difficult to achieve. There appears to be no precise definition of the overall CO2 capture rate required to justify changing the prefix from grey to blue. Maximum capture rates are reported to be up to 70% for SMR (or up to 90% if post-combustion CO2 capture is included) and over 90% for ATR.

The GHG footprint of grey hydrogen is a function of the CO2 output from the water-gas shift reaction, the GHG footprints of the steam and oxygen inputs, and the fugitive emissions. A datum value of 91 gCO2e/MJ of hydrogen (328 gCO2e/kWh) has been identified to represent the GHG footprint of SMR hydrogen, with a proposed threshold value of 36.4 gCO2e/MJ, below which hydrogen may be described as ‘low carbon’. The latter equates to a 60% reduction in GHG emissions, leaving a further 40% to be achieved if net-zero hydrogen is to be produced.

## 2.3 Blue hydrogen [8]

Blue hydrogen is produced from fossil fuels however CO2 is captured and stored. Blue hydrogen is characterized by upstream methane emissions as well as an imperfect downstream process of capturing and sequestering CO2. Therefore, it has a residual GHG footprint, which means of itself it isn’t compatible with achieving the net-zero objective. Most modelling studies appear to have assumed capture rates of 90–98% and overlooked or underestimated the global warming impact of fugitive emissions. In general, there is a lack of data concerning CO2 capture rates for blue hydrogen production in practice, partly because CCS still requires further technological development, especially for large-scale systems. To achieve a zero-GHG footprint for blue hydrogen requires so-called ‘negative emissions’ to be captured in the correct amounts to compensate for its residual emissions. This necessitates implementing extra measures, which serve to increase the cost of blue hydrogen (e.g. afforestation, or CCS combined with biogenic energy conversion or direct air capture). Yet no colour prefix appears to have been attributed to blue hydrogen production when combined with negative emissions production, but clearly this coupling is essential if blue hydrogen is to play a role in the future climate-neutral energy system.

## 2.4 Turquoise hydrogen [9]

Hydrogen production via the pyrolysis of a fossil fuel has been described as ‘turquoise’ hydrogen. Turquoise hydrogen can be extracted by using the thermal splitting of methane via methane pyrolysis. The process, though at the experimental stage, remove the carbon in a solid form instead of CO2 gas.

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[8] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

[9] Hydrogen colours codes - H2 Bulletin

### 2.5 Purple Hydrogen [10]

Purple hydrogen is made using nuclear power and heat through combined chemo thermal electrolysis splitting of water.

### 2.6 Pink Hydrogen [10]

Pink hydrogen is generated through electrolysis of water by using electricity from a nuclear power plant.

### 2.7 Red Hydrogen [10]

Red hydrogen is produced through the high-temperature catalytic splitting of water using nuclear power thermal as an energy source.

### 2.8 White Hydrogen [10]

White hydrogen refers to hydrogen occurring in its (rare) natural form. Also refers to hydrogen produced as a byproduct of industrial processes.

### 2.9 Green Hydrogen [11]

Renewable hydrogen is produced when the electrolyser is fed with renewable electricity – this is commonly referred to as 'green' hydrogen. The production of green hydrogen is not capacity limited. Some 173.000 TW of solar energy strikes the Earth

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[10] Hydrogen colours codes - H2 Bulletin

[11] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

continuously, which is approximately 10.000 times the global energy consumption. Simplistically the latter could be met by covering 8% of the Sahara Desert with solar power sources, or 1.5% of the Pacific Ocean with wind power sources. Green hydrogen production of itself produces net-zero hydrogen, without requiring CCS or the capture of negative emissions.

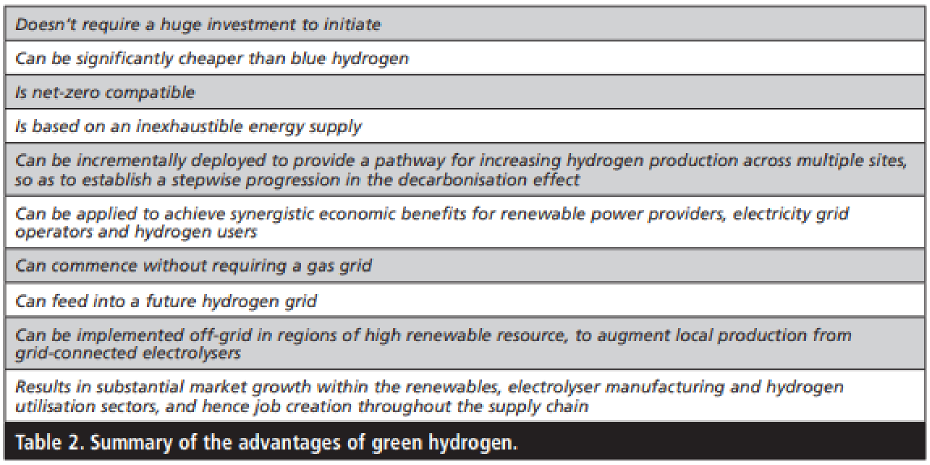
To achieve a zero-GHG footprint for green hydrogen requires the electrolyser to be directly connected to a renewable power source. Alternatively, if the electrolyser only uses renewable electricity purchased via the electricity grid or operates in a synchronous manner with grid-connected renewables, then arguably it also produces green hydrogen. In some regions (e.g. Norway, Scotland, British Columbia, north-eastern Brazil, Uruguay, New Zealand) grid-connected electrolysers will already yield hydrogen of zero, or near zero, GHG footprint. However, in most industrialised countries the current average GHG footprint of grid electricity prevents this. Therefore, policies are needed to facilitate green hydrogen production on-grid, so the synergies between greater renewables integration and electrolyser operation can be realised.

Several definitions of green hydrogen have been proposed and discussed in the literature:

- The aforementioned GHG intensity threshold of 36.4 gCO2e/MJ (see para. 2.2 Grey Hydrogen) enables hydrogen produced predominantly, as opposed to entirely, from renewable electricity to be classified as green.
- An alternative threshold has been suggested where the green prefix may be used provided the GHG footprint of the electrolytic hydrogen is <25% of that applying to the fuel it displaces.

However, at present there is no agreed threshold or auditing methodology to confer the green prefix on hydrogen produced by grid-connected electrolysers, which amounts to both a strategy gap and a policy gap. This issue is currently being addressed by the European Commission in the finalization of Renewable Energy Directive II.

Because renewable generation is weather dependent it is often out of time phase with energy demand. Accordingly, green hydrogen production is ultimately constrained by the operating patterns and capacity factors of renewable power sources. Fortunately, hydrogen can be stored cheaply at scale (unlike electricity) and so storage is a central consideration in the wider implementation of green hydrogen solutions. The geological storage of green hydrogen in salt caverns and suitable underground stores can provide a renewable energy 'lung' for the entire energy system. For these reasons there is vast potential in locating green hydrogen production in regions of high renewable resource (e.g. with offshore wind farms in the North Sea and with solar farms in North Africa), interconnecting them with subterranean stores and conveying hydrogen to the points of demand.



| |
|---|
| *Doesn't require a huge investment to initiate* |
| *Can be significantly cheaper than blue hydrogen* |
| *Is net-zero compatible* |
| *Is based on an inexhaustible energy supply* |
| *Can be incrementally deployed to provide a pathway for increasing hydrogen production across multiple sites, so as to establish a stepwise progression in the decarbonisation effect* |
| *Can be applied to achieve synergistic economic benefits for renewable power providers, electricity grid operators and hydrogen users* |
| *Can commence without requiring a gas grid* |
| *Can feed into a future hydrogen grid* |
| *Can be implemented off-grid in regions of high renewable resource, to augment local production from grid-connected electrolysers* |
| *Results in substantial market growth within the renewables, electrolyser manufacturing and hydrogen utilisation sectors, and hence job creation throughout the supply chain* |

**Table 2. Summary of the advantages of green hydrogen.**

## 2.10 Fugitive methane emissions [12]

Producing grey, turquoise or blue hydrogen from natural gas also causes methane leaks upstream of the production process, due to the exploration and long-distance transportation of natural gas. These so-called 'fugitive' emissions have a substantial global warming impact, which is additional to the CO2 emissions resulting from converting natural gas to hydrogen.

Atmospheric methane concentrations have been rising since 2007 and accelerating in recent years. Satellites and more precise measurement technology have revealed significant methane leaks from the oil & gas infrastructure. It has been estimated that 2.3% of US gas production is emitted to the atmosphere, which when considered on a

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[12] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

20-year time base brings about radiative forcing of a similar magnitude to that caused by all of the CO2 emissions resulting from US gas combustion.

Thus, there is an urgent need to both reduce fugitive methane emissions and avoid designing them into future hydrogen strategies (e.g. the European Commission recently set out its plan to reduce anthropogenic and biogenic methane emissions).

### 2.11 Terminology [13]

- «Electricity-based hydrogen» refers to hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), regardless of the electricity source. The full life-cycle greenhouse gas emissions of the production of electricity-based hydrogen depends on how the electricity is produced.
- «Renewable hydrogen» is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources. The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero.

Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.

- «Clean hydrogen» refers to renewable hydrogen
- «Fossil-based hydrogen» refers to hydrogen produced through a variety of processes using fossil fuels as feedstock, mainly the reforming of natural gas or the gasification of coal. This represents the bulk of hydrogen produced today. The life-cycle greenhouse gas emissions of the production of fossil-based hydrogen are high.
- «Fossil-based hydrogen with carbon capture» is a subpart of fossil-based hydrogen, but where greenhouse gases emitted as part of the hydrogen production process are captured. The greenhouse gas emissions of the production of fossil-based hydrogen with carbon capture or pyrolysis are lower than for fossil-fuel based

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[13] European Commission, «Questions and answers: A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

hydrogen, but the variable effectiveness of greenhouse gas capture (maximum 90%) needs to be taken into account.

- «Low-carbon hydrogen» encompasses fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production.
- «Hydrogen-derived synthetic fuels» refer to a variety of gaseous and liquid fuels on the basis of hydrogen and carbon. For synthetic fuels to be considered renewable, the hydrogen part of the syngas should be renewable. Synthetic fuels include for instance synthetic kerosene in aviation, synthetic diesel for cars, and various molecules used in the production of chemicals and fertilisers. Synthetic fuels can be associated with very different levels of greenhouse gas emissions depending on the feedstock and process used. In terms of air pollution, burning synthetic fuels produces similar levels of air pollutant emissions than fossil fuels.

## 2.12 Overall comparison/conclusion [14]

There are choices to be made concerning the amounts and types of hydrogen that will be produced, or imported, to achieve a climate-neutral energy system. Some nations have recently declared that they will focus on green hydrogen (e.g. France, Germany, Portugal, Spain), some may produce yellow hydrogen, and some may wish to produce or import blue hydrogen. The main decision appears to be between blue and green hydrogen, and many believe the choice will be made solely on economic grounds.

There are relatively few independent and detailed comparisons of blue and green hydrogen costs in the literature, but several misconceptions exist such as ‘blue is cheaper than green’, ‘blue is required to enable green’, and ‘blue should be adopted first, because green will not be economic until later’. In general, this subject warrants careful analysis if effective cost comparisons are to be made. Any economic assessment of hydrogen production methods should foremost ensure that it is comparing like with

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[14] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

like. It is fundamentally incorrect to compare blue and green hydrogen unless they are of identical purity, pressure and GHG footprint. Analyses should ensure parity values apply for each of these parameters. Clearly any steps involving purification, compression or GHG footprint adjustment serve to increase hydrogen costs.

In general, there are several areas where potential errors can occur, or a lack of transparency can cast doubt over the cost estimates:

- If the points of production and consumption are co-located for some production methods but not for others, comparisons are invalid unless the interconnecting distribution method is accounted for.
- The assumptions concerning leakage rates into the atmosphere and global warming potentials (for methane, carbon dioxide and hydrogen) associated with the production and any implicit distribution of hydrogen.
- The assumptions concerning embodied carbon, CO2 capture rate, fugitive emissions and negative emissions for netting off residual emissions.
- Comparing the cost of hydrogen produced by MW versus GW scale plant, because economies of scale apply.

Blue hydrogen costs depend mainly on:

- the price of natural gas
- the cost of the reformer
- the cost of implementing the required CO2 recovery facilities
- the cost of transport and storage/utilization facilities and
- the operating costs for the combined system of natural gas reformation and CCS
- if the hydrogen is to be of zero-GHG footprint there are additional costs in generating/capturing the required negative emissions. To produce low-cost hydrogen, CCS must be applied at large scale, and preferably fed with CO2 from a number of large-scale reformers. It is thus a centralised approach that requires some means of distributing hydrogen in large amounts to the points of use.

In general, there would appear to be three prerequisites for establishing blue hydrogen.

- First, a large hydrogen demand needs to exist that can consume hydrogen at scale on a reasonably continuous basis.

- Secondly, some form of hydrogen infrastructure is required to interconnect the points of supply and demand.
- Thirdly, a carbon dioxide infrastructure is required to pipe or ship the CO2 to the storage sites, for which an economic value needs to be placed on the CO2.

On the demand side, the two main options for blue hydrogen in the short term are:

- Large industrial clusters that currently use grey hydrogen, or
- A natural gas grid into which blue hydrogen admixtures can be injected.

Advantageously both of these can be achieved with a minimum of hydrogen transmission infrastructure if the reformers are appropriately located. In the longer term, the main outlet for blue hydrogen is an extensive gas grid that enables numerous end-users to combust hydrogen rather than natural gas. However, in all cases there needs to be an income stream or ‘customer’ for the CO2. To date this has been solved by using CO2 for enhanced oil recovery (EOR), to extract crude oil that cannot be extracted otherwise. Unfortunately, EOR has limited CO2 storage capacity and only partially offsets the costs of CCS, and when the oil is used it simply leads to more CO2 emissions!

Therefore, the economic dilemma for blue hydrogen is the need to establish a suitable price for the waste CO2 stream. If it can be used as a feedstock to synthesise chemicals, then it can have value (as implied by the recent adoption of the term CCUS, to impart that the CO2 may be utilised rather than just accumulated). However, such an approach invokes a need to establish the production of synthetic fuels and chemicals at a sufficient scale to make use of the CO2, which amplifies the required capital investment. By comparison, there is no need to provide an income stream for the oxygen that is usually vented to atmosphere from an electrolyser, because oxygen isn’t a global warming gas and doesn’t need to be sequestered. Any commercial applications of electrolytic oxygen are therefore a genuine economic upside for green hydrogen.

Usually, the producer pays to dispose of any waste associated with the production process. If this principle is applied to blue hydrogen production, then its cost will be substantially greater than that of grey hydrogen (which in turn is significantly more expensive than natural gas). Although economies of scale will be realised if blue hydrogen is widely adopted, the handling and storage of the CO2 by-product will always have a large impact on costs. So, the adoption of CCS will require subsidies if the fossil fuel sector is to produce blue hydrogen at low cost.

According to the International Monetary Fund (IMF), fossil fuels receive 85% of all existing subsidies worldwide (amounting to 6.3% of global GDP), so additional subsidies for CCS would appear difficult to justify. The European Academies Science Advisory Council (EASAC) recently recommended that governments should remove subsidies, taxes, levies and other incentives for fossil fuels, because they continue to distort energy markets and limit the potential growth of markets for renewable hydrogen and synthetic fuels. No government has yet introduced a subsidy scheme for blue hydrogen production. Indeed, it appears that blue hydrogen is increasingly being advocated as a temporary measure in order to make use of existing investments in oil & gas assets, rather than as an environmentally sustainable long-term solution for 2050 and beyond.

Green hydrogen production can be applied via a decentralised approach close to the points of demand and at a greater scale via a more centralised approach (e.g. at the points of power generation, or upstream of bottlenecks in the electricity grid). On the demand-side, the ability to step up the installed electrolyser capacity at a given site is particularly useful for increasing the degree of decarbonisation over time. It enables hydrogen supply and demand to grow in unison and spreads the investment costs for stakeholders, reducing working capital requirements. On the supply-side, electrolysers can offer a firm market for new renewables and a flexible load for grid operators (from whom an income can be earned for providing frequency response and negative reserve services). It also offers renewable power companies the opportunity to create a new product that is storable. Hence the green hydrogen approach. provides benefits to several stakeholders, and importantly it does not produce a downstream waste.

Green hydrogen costs depend mainly:

- on the price of the input electricity and
- the load factor of the electrolyser

As renewable power sources are upscaled and their deployment increases, unit costs decrease and capacity factors increase. This results in improved availability and lower-cost renewable electricity. Furthermore, as the grid integrates more and more renewables, the value of renewable electricity during low demand periods decreases to a very low level, or even becomes negative when supply exceeds demand. The ability of green hydrogen production to coincide with low demand periods therefore provides both a new market for the renewable power providers, which is out of time phase with the conventional electricity demand profile, and a new flexible load for helping the electricity system operator to balance the grid. These synergistic benefits will result in lower-cost green hydrogen as the integration of renewables increases.

Electrolyser technology is currently being upscaled and cost-reduced in preparation for volume production. Ongoing efforts to optimise membrane-electrode assemblies (MEAs), increase the active area per cell, increase the number of cells per stack, increase current density without compromising efficiency, reduce balance of plant (BOP) costs, reduce power conversion costs, modularise system designs, reduce assembly time, semi-automate manufacturing and achieve supply chain efficiencies will culminate in substantial reductions in the unit costs of electrolysers across the next few years.

This trend in electrolyser cost, in combination with the aforementioned trend in electricity cost, enables green hydrogen production to be characterised by a progressively decreasing unit cost over time. For a Europe-wide hydrogen grid in 2050, unit costs as low as 11 €/MWh have been predicted for green hydrogen, which is cheaper than natural gas, while blue hydrogen remains above 40 €/ MWh. If hydrogen is to be widely employed as a combustion fuel, the ability of green hydrogen to ultimately achieve a similar unit cost to that of natural gas is a key point of distinction.

Blue hydrogen production is both the potential savior of the existing fossil fuel supply chain and a means for increasing natural gas sales per TWh of final energy consumption (due to the energy losses associated with hydrocarbon reformation and CCS). For several years suppliers of natural gas, gas grid operators and manufacturers of combustion appliances and heat engines have been advocating for blue hydrogen production. For any nation that is highly dependent on importing natural gas, the blue hydrogen approach helps the overseas gas supplier and stakeholders in the existing supply chain, at the expense of making the country a geological accumulator for the waste CO2 produced by reforming natural gas. There is also a potential conflict of interest between the country supplying the natural gas (e.g. Norway or Russia) and the country that stores the CO2 caused by the blue hydrogen production process.

Advocating blue hydrogen and the adoption of CCS in order to perpetuate the use of natural gas is a controversial option. Blue hydrogen production needs to be done at scale, requires large investments from the outset, takes time to introduce, requires a substantial sink for the hydrogen, and has a number of uncertainties with respect to CCS and who pays for the CO2 disposal, which makes it difficult to justify. The choice for the operator of a natural gas reformer in the transition to a climate-neutral energy system is quite stark: either sequester the CO2 and net off the residual emissions or shut it down. This applies to existing reformers and any future installations. In essence, blue hydrogen is an end-of-pipe technical fix with dubious economic and environmental credentials. Its primary purpose is to protect incumbent organizations in the existing supply chain, so that they can continue to exploit investments in natural gas exploration and infrastructure.

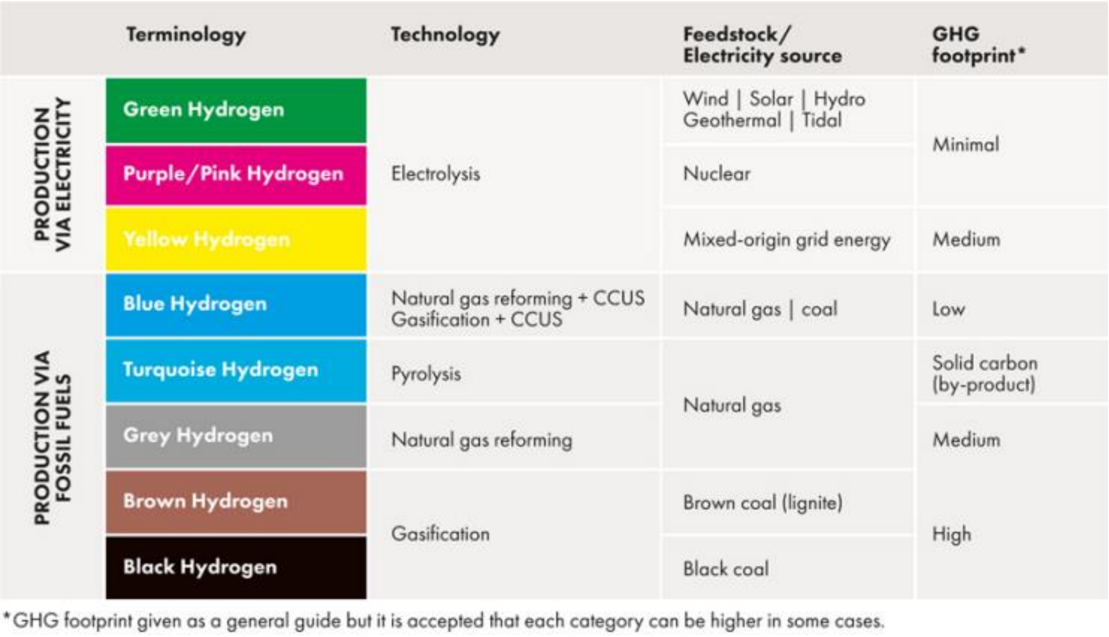
Studies to date aren’t clear about the cost of producing net-zero blue hydrogen. In general, it appears that green hydrogen will soon be cheaper than blue hydrogen, then cheaper than grey hydrogen, and in the long term potentially cheaper than natural gas. For example, it has been predicted that green hydrogen will be cheaper than grey hydrogen by 2030, and that by 2050 green hydrogen will be less than one-third of the cost of blue hydrogen.

Clearly the green hydrogen approach circumvents the uncertainties, complexities and costs associated with blue hydrogen production and CCS. Moreover, the characteristic cost down curve for green hydrogen suggests that taxpayer subsidies, which will be required to avoid market failure during the early years, can in time decline to zero. When compared with blue hydrogen, green hydrogen offers several advantages. These are important factors for governments to consider in planning the transition to a climate-neutral energy system.

# CHAPTER 3: A COMPARATIVE OVERVIEW OF HYDROGEN PROCESSES

## 3.1 Introduction

Hydrogen is the most common element on earth, but it still must be produced as it exists only in combination with other elements. Multiple processes and energy sources can be used to isolate hydrogen, and to best understand all the different production means, as already said, a colour coded nomenclature is commonly used [Table 4]. In all cases it takes energy to create pure hydrogen. For that reason, the climate change impact of using it depends on the carbon footprint of the energy used to produce it. Sources with a lower GHG footprint are favoured for decarbonisation.



| | Terminology | Technology | Feedstock/ Electricity source | GHG footprint* |
|---|---|---|---|---|
| PRODUCTION VIA ELECTRICITY | Green Hydrogen | Electrolysis | Wind \| Solar \| Hydro<br>Geothermal \| Tidal | Minimal |
| | Purple/Pink Hydrogen | | Nuclear | |
| | Yellow Hydrogen | | Mixed-origin grid energy | Medium |
| PRODUCTION VIA FOSSIL FUELS | Blue Hydrogen | Natural gas reforming + CCUS<br>Gasification + CCUS | Natural gas \| coal | Low |
| | Turquoise Hydrogen | Pyrolysis | Natural gas | Solid carbon (by-product) |
| | Grey Hydrogen | Natural gas reforming | | Medium |
| | Brown Hydrogen | Gasification | Brown coal (lignite) | High |
| | Black Hydrogen | | Black coal | |

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

*Table 3: The Hydrogen Colour Rainbow (Source: Global Energy Infrastacture, 2021)*

The technologies mentioned above, are described analytically below.

## 3.2 H2 production from fossil fuels

### 3.2.1 Hydrocarbon reforming methods – Steam reforming method (Grey & Blue Hydrogen)

Steam-methane reforming is a widely used method of commercial hydrogen production. Commercial hydrogen producers and petroleum refineries use steam-methane reforming to separate hydrogen atoms from carbon atoms in methane (CH4). In steam-methane reforming, high-temperature steam (1,300°F to 1,800°F) under 3–25 bar pressure (1 bar = 14.5 pounds per square inch) reacts with methane in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Natural gas is the main methane source for hydrogen production by industrial facilities and petroleum refineries.

SMR is a high-temperature endothermic process that first requires trace sulphur compounds to be removed from the natural gas to avoid catalyst poisoning, and then substantial inputs of heat (at temperatures up to 1000°C) and water in the form of superheated steam:

$$CH4 + H2O \rightarrow CO + 3H2,\ \Delta H = 206\ KJ\ /\ mol$$ [15]

The efficiency of steam reforming method depends on the steam temperature and the type of hydrocarbon. So, it ranges in the area 65 - 75%.

It is the method most used today for the production of H2, as it has the lowest cost. The hydrogen produced is so-called "grey" hydrogen, precisely because of the production of greenhouse gases produced during this process.

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[15] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

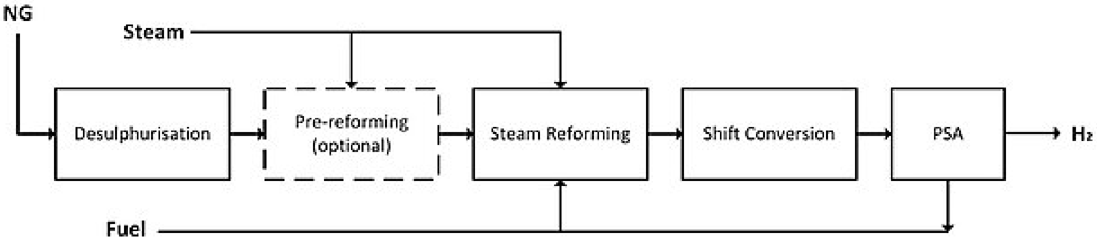

*Figure 4: Depiction of the general process flow of a typical steam reforming plant.*

However, since this method produces considerable amounts of greenhouse gases CO2 capture technologies (Carbon capture and storage CCS) should be used in the second phase which are already developed. In this case we are now talking about blue hydrogen, given the much smaller environmental burden created by its production.

The main ways of capturing the CO2 produced are:

- The geological ways of its storage, where CO2 is channeled into geological formations either of depleted gas and oil fields, or in salty aquifers of great depth. Other alternative methods of geological storage are in coal seams and basalt rocks.
- The channeling of CO2 into an underground oil extraction site (the enhanced oil recovery technique), in order to compress and cause the rise of oil, except that this method is not environmentally neutral, since part of the CO2 that is channeled underground rises to the surface with oil.
- By natural degradation of CO2 when it is channeled into algae and bacteria.
- By reaction of CO2 with metal oxides and formation of carbonate minerals such as magnesite and calcite.

All the above methods are in the initial stages of implementation, there is not much experience of their application yet and of course the problem they present is their cost.

### 3.2.2 Hydrocarbon pyrolysis (Turquoise Hydrogen)

Hydrogen may also be generated via the pyrolysis of a fossil fuel, where the by-product is carbon. The pyrolysis of natural gas to produce carbon black is well known:

$$CH_4 \rightarrow 2H_2 + C$$

Producing hydrogen by pyrolysis involves the thermal decomposition, catalytic decomposition or plasma decomposition of methane.

Pyrolysis avoids the need to sequester $CO_2$ in order to produce hydrogen with a low GHG footprint, provided that the by-product is utilised (e.g. for building and construction materials). Hydrogen production via the pyrolysis of a fossil fuel has been described as ‘turquoise’ hydrogen [16].

## 3.3 H2 production from renewable sources

### 3.3.1 Hydrogen from biogenic sources - Biomass process (No color prefix)

Hydrogen may be generated by biomass fermentation, gasification, reforming, pyrolysis and bio-photolysis processes. The potential capacity of biogenic hydrogen is limited, because the amount of indigenous biomass available usually amounts to only a small fraction of a country’s energy needs. For the EU it has been estimated that the potential biomass resource amounts to roughly 10% of Europe’s final energy consumption. Also, with a rising global population there is an overarching conflict of interest between growing plants to provide fuel and food production.

The $CO_2$ produced when extracting hydrogen from biogenic sources may enter the atmosphere (which is arguably acceptable, provided the life cycle analyses and auditing processes verify that the production process is carbon-neutral in practice), or captured via CCS. If biogenic hydrogen production is combined with CCS then advantageously it produces negative-carbon hydrogen. Such an approach may be implemented in its own right, in which case the ultimate scale of the biomass resource will dictate the scale of CCS required. Alternatively, it may be viewed as a means of netting off the residual

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[16] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

emissions of blue hydrogen production (e.g. by reforming streams of biomethane and natural gas in the required proportions).

At present, no significant production of biogenic hydrogen is occurring. No colour prefix appears to have been attributed to biogenic hydrogen, with or without CCS being applied [17].

### 3.3.2 Hydrogen from water electrolysis - Water splitting (Green Hydrogen)

Hydrogen may be produced from water electrolytically, photo-electrolytically, or thermo-electrolytically. The latter two methods are still R&D topics and hampered by low conversion efficiencies, but water electrolysis is well proven and can convert electricity to hydrogen at an efficiency of 70–80% (higher heating value, HHV) [17].

#### 3.3.2.1 Electrolysis

Electrolysis is a low-temperature single step process that requires two inputs, namely electricity and water, and produces two outputs: high-purity hydrogen and oxygen. Electrolysers may follow steady-state or transient operating regimes, with proton exchange membrane (PEM) electrolysers offering particularly rapid response times. The water electrolysis reaction may be written:

$$2H2O \rightarrow 2H2 + O2$$

Clearly there is no contamination from hydrocarbons in electrolytic hydrogen production. It produces hydrogen of >99.95% purity. There is no association between electrolytic hydrogen production and CO2 or methane emissions (and hence

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[17] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

requirement for CCS), unless the electrolysers consume electricity generated by a fossil fuel power plant [18].

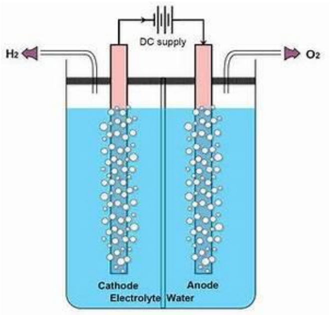

*Figure 5: Water-electrolysis*

### 3.3.2.2 Photo-electrolysis

A promising future method of hydrogen production is photo-electrolysis, which uses solar energy to extract hydrogen directly from water. Photo-electrolysis integrates solar energy collection and water electrolysis into a single photoelectrode. This device eliminates the need for a separate power generator and electrolyzer, reducing overall costs and increasing efficiency.

Photo-electrolysis systems are still in the experimental stage. However, photo-electrolysis will become an important means to future hydrogen production because it is powered by renewable solar energy.

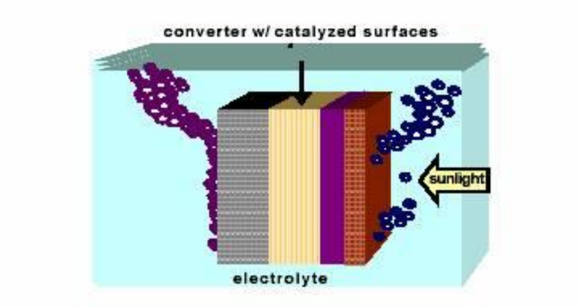

*Figure 6: Photo-electrolysis*

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[18] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

#### 3.3.2.3 Thermolysis

Thermochemical water splitting uses high temperatures (from concentrated solar power or from the waste heat of nuclear power reactions) and chemical reactions to produce hydrogen and oxygen from water. This is a long-term technology pathway, with potentially low or no greenhouse gas emissions. Thermochemical water splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen.

## 3.4 Hydrogen from water electrolysis using nuclear power (Pink Hydrogen)

Electrolytic hydrogen can also be produced from nuclear power, and this has been referred to as ‘pink’ hydrogen. The electrolysers may be operated to minimize the curtailment of nuclear power stations, and if the technologies are co-located hydrogen can be produced at scale. For countries with significant installed capacities of nuclear power, substantial amounts of pink hydrogen could be produced at regional level for industrial clusters or a future hydrogen grid.

Combining large electrolysis plants with nuclear power plants allows a relatively high baseload of power generation year-round, by using the electrolysers as a flexible demand-side load. This approach could provide significant operational advantages both for existing nuclear power stations and micro nuclear reactors, which are currently under development by Rolls-Royce and other companies worldwide [19].

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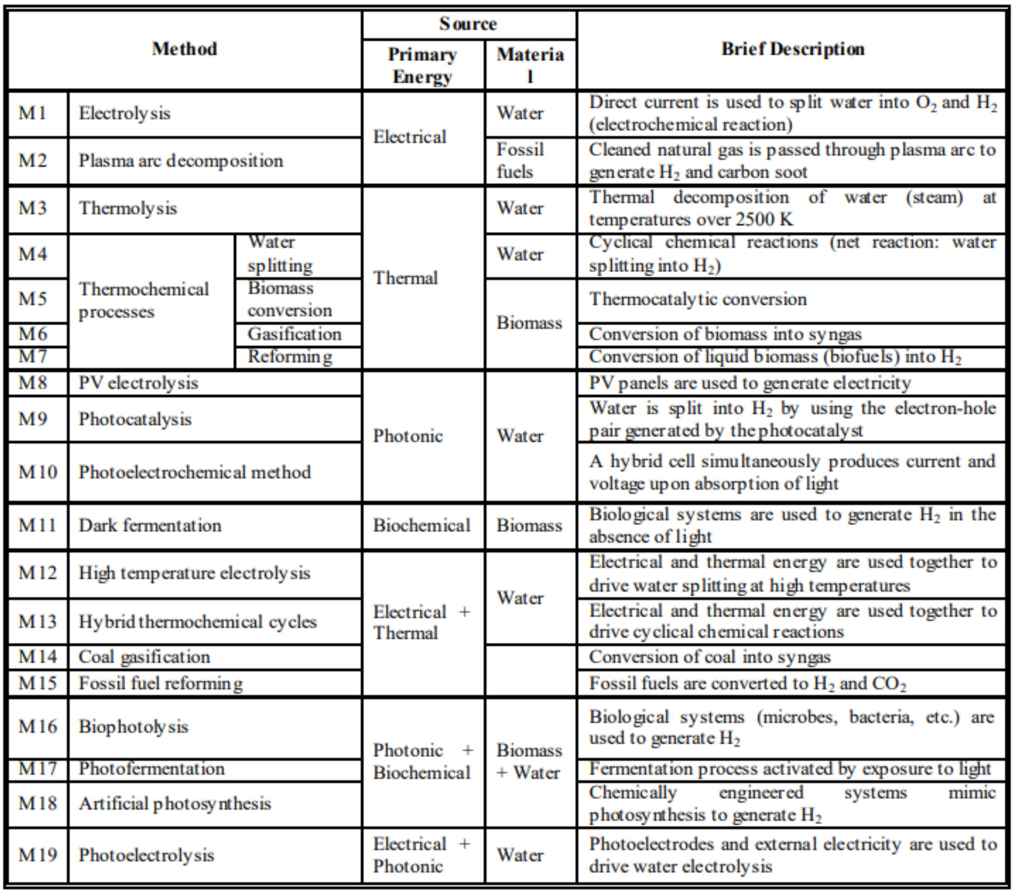
[19] Marcus Newborough and Graham Cooley, ITM Power Plc, Sheffield, UK, «Developments in the global hydrogen market: The spectrum of hydrogen colours», November 2020

## 3.5 Overall comparison/conclusions [20]

Given the current state of technology, natural gas-based hydrogen production in large industrial plants seems to be the cheapest method available. In energy services industry, secured supply is an important criterion which should be addressed by the hydrogen economy as well. Optimizing capital, operating and maintenance costs as well as developing systems with high efficiencies, low impurity levels, and emissions, and increasing the role of renewable energies are some of the critical challenges of the hydrogen economy.

At the following tables an overview of hydrogen production methods by primary energy and material source as well as the key benefits and critical challenges of selected hydrogen production methods are given:



| Method | | | Source | | Brief Description |
|---|---|---|---|---|---|
| | | | Primary Energy | Material | |
| M1 | Electrolysis | | Electrical | Water | Direct current is used to split water into $O_2$ and $H_2$ (electrochemical reaction) |
| M2 | Plasma arc decomposition | | | Fossil fuels | Cleaned natural gas is passed through plasma arc to generate $H_2$ and carbon soot |
| M3 | Thermolysis | | Thermal | Water | Thermal decomposition of water (steam) at temperatures over 2500 K |
| M4 | Thermochemical processes | Water splitting | | Water | Cyclical chemical reactions (net reaction: water splitting into $H_2$) |
| M5 | | Biomass conversion | | Biomass | Thermocatalytic conversion |
| M6 | | Gasification | | | Conversion of biomass into syngas |
| M7 | | Reforming | | | Conversion of liquid biomass (biofuels) into $H_2$ |
| M8 | PV electrolysis | | Photonic | Water | PV panels are used to generate electricity |
| M9 | Photocatalysis | | | | Water is split into $H_2$ by using the electron-hole pair generated by the photocatalyst |
| M10 | Photoelectrochemical method | | | | A hybrid cell simultaneously produces current and voltage upon absorption of light |
| M11 | Dark fermentation | | Biochemical | Biomass | Biological systems are used to generate $H_2$ in the absence of light |
| M12 | High temperature electrolysis | | Electrical + Thermal | Water | Electrical and thermal energy are used together to drive water splitting at high temperatures |
| M13 | Hybrid thermochemical cycles | | | | Electrical and thermal energy are used together to drive cyclical chemical reactions |
| M14 | Coal gasification | | | | Conversion of coal into syngas |
| M15 | Fossil fuel reforming | | | | Fossil fuels are converted to $H_2$ and $CO_2$ |
| M16 | Biophotolysis | | Photonic + Biochemical | Biomass + Water | Biological systems (microbes, bacteria, etc.) are used to generate $H_2$ |
| M17 | Photofermentation | | | | Fermentation process activated by exposure to light |
| M18 | Artificial photosynthesis | | | | Chemically engineered systems mimic photosynthesis to generate $H_2$ |
| M19 | Photoelectrolysis | | Electrical + Photonic | Water | Photoelectrodes and external electricity are used to drive water electrolysis |

*Table 4: Overview of hydrogen production methods by primary energy and material source*

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[20] Review and evaluation of hydrogen production methods for better sustainability, Ibrahim Dincer and Canan Acar

| Fossil Fuel Reforming | Biofuel Reforming | Coal and Biomass Gasification | Thermochemical Method | Water Electrolysis | Photoelectrochemical Method | Biological Method |
|---|---|---|---|---|---|---|
| Critical Challenges | | | | | | |
| High capital costs | High capital costs | High reactor costs | Cost effective reactor | Low system efficiency | Effective photocatalytic material | Efficient microorganisms for sustainable production |
| Design | High operation and maintenance costs | System efficiency | Long-term technology | High capital costs | Low system efficiency | Optimal microorganism functionality |
| High operation and maintenance costs | Design | Feedstock impurities | Effective and durable materials | System integration | Cost effective reactor | Reactor material selection |
| | Feedstock quality | Carbon capture and storage | | Design issues | Long-term technology | Long-term technology |
| Major R&D Needs | | | | | | |
| Efficiency and cost | Hydrogen yield and efficiency | Low cost and efficient purification | Robust, low cost materials | Durable and cheap materials | Durable and efficient photocatalyst | Microorganism functionality |
| Low cost and efficient purification | Low temperature production | Co-fed gasifiers | Ease of manufacture and application | Corrosive-resistant membranes | Low cost materials | New organisms |
| Feedstock pre-treatment | Low cost and efficient purification | Carbon capture and storage | System optimization | Durable, active, and cheap catalysts | Active, stable, and cheap supporting materials | Inexpensive methods |
| Optimization | Optimization | Hydrogen quality | High volume, low cost, flexible system design | Large scale applications | High volume production | Low cost and durable material |
| Automated process control | Regional best feedstock | Cost of feedstock preparation | Efficient heat transfer | Storage and production rate | System control | System optimization |
| Reliability | Feedstock pre-treatment | Tolerance for impurities | Reliability | Reliability | Power losses | High capacity and low cost systems |
| Key Benefits | | | | | | |
| Most viable approach | Viability | Low cost syngas production | Clean and sustainable | No pollution with renewable energy sources | Low operation temperature | Clean and sustainable |
| Lowest current cost | Existing infrastructure | Abundant and cheap feedstock | Recycled chemicals | Existing infrastructure | Clean and sustainable | Tolerant of diverse water conditions |
| Existing infrastructure | | | | Integration with fuel cells | | Self sustaining |

*Table 5: Key benefits and critical challenges of selected hydrogen production methods*

The current levels of maturity for hydrogen production pathways are shown in Figure 7 below. The most established technology options for producing hydrogen from renewable energy sources are water electrolysis and steam reforming of biomethane/biogas with carbon capture and utilisation/storage (CCU/CCS). Less mature pathways are biomass gasification and pyrolysis, thermochemical water splitting, photocatalysis, supercritical water gasification of biomass, and combined dark fermentation and anaerobic digestion [21].

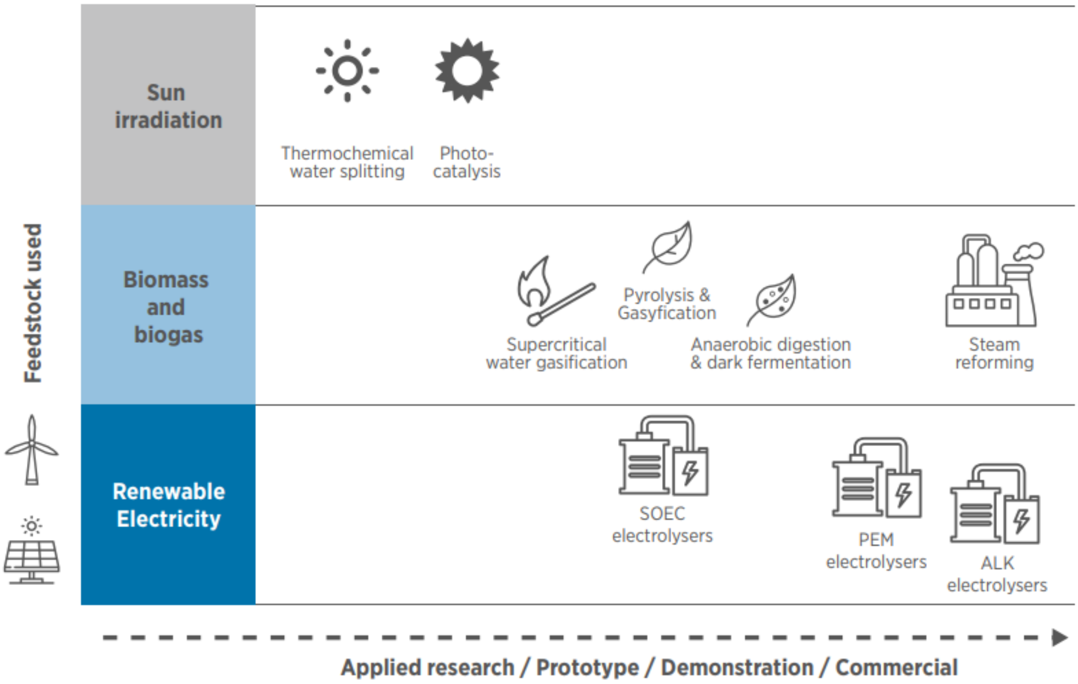

*Figure 7: Renewable hydrogen production pathways and current levels of maturity*

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[21] IRENA, Hydrogen from renewable power technology outlook for the energy transition, September 2018

# CHAPTER 4: GREEN HYDROGEN, EU POLICIES & THE EUROPEAN GREEN DEAL

## 4.1 European Green Deal [22], [23], [24]

In late 2019, the European Commission (EC) presented the European Green Deal, outlining the main policy initiatives for reaching net-zero greenhouse gas (GHG) emissions by 2050. The Green Deal identifies clean hydrogen as a priority area for achieving carbon neutrality by 2050. There are two aspects: firstly, the European Union (EU) currently uses approximately 9.7 million tonnes (Mt) of hydrogen annually and this needs to be decarbonised. Secondly, hydrogen is considered a key input to the future energy system as a flexible energy carrier for industry and transport, helping to reduce GHG and particle emissions.

On 8 July 2020 the European Commission proposed a communication for an EU hydrogen strategy, which is part of the ‘European Green Deal’. This will be coupled with a broader EU strategy on systems integration, which means linking the various energy carriers, electricity, heat, cold, gas, solid and liquid fuels, with each other and with the end-use sectors, such as buildings, transport or industry.

The path set by the EU Hydrogen Strategy is divided into three phases. Each phase sets a specific objective to be achieved within the relevant phase. The EU summarises the objectives for each phase as follows:

- Phase 1 (2020-24): the objective is to decarbonise existing hydrogen production for current uses such as the chemical sector and promote it for new applications. This phase relies on the installation of at least 6 GW of renewable hydrogen

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[22] European Commission, «Questions and answers: A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

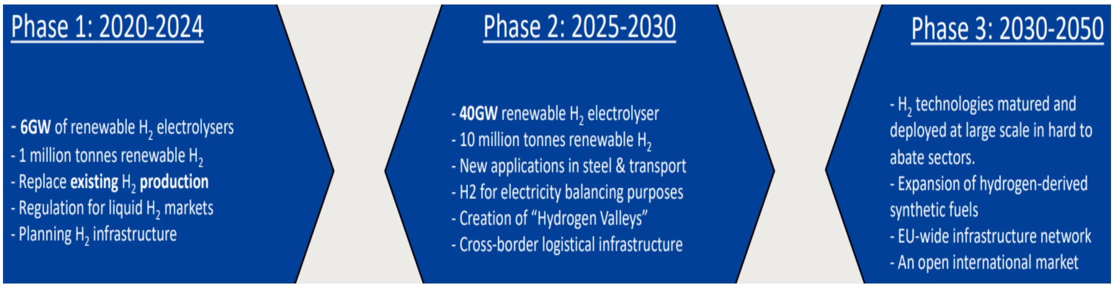
[23] Ruven Fleming (2021) Clean or renewable – hydrogen and power-to-gas in EU energy law, Journal of Energy & Natural Resources Law, 39:1, 43-63, DOI: 10.1080/02646811.2020.1795382

[24] G. Kakoulaki, I. Kougias, N. Taylor, F. Dolci, J. Moya, A. J¨ ager-Waldau, «Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables».

electrolysers in the EU by 2024 and producing up to one million tonnes of renewable hydrogen. In this phase, EU policy focus will be on laying down the regulatory framework for a liquid and well-functioning hydrogen market and on incentivizing both supply and demand in lead markets, including through bridging the cost gap between conventional solutions and renewable and low-carbon hydrogen and through appropriate State aid rules.

- Phase 2 (2024-30): hydrogen needs to become an intrinsic part of an integrated energy system with a strategic objective to install at least 40 GW of renewable hydrogen electrolysers by 2030 and the production of up to 10m tonnes of renewable hydrogen in the EU. Hydrogen use will then gradually expand into new sectors, including steel-making, trucks, rail and some maritime transport applications. It will still mainly be produced close to the user or the renewable energy sources, in local ecosystems.

  The Commission will consider various options for incentives at EU level, including the possibility of minimum shares or quotas of renewable hydrogen or its derivatives in specific end-use sectors (for instance certain industries as the chemical sector, or transport applications), allowing demand to be driven in a targeted way. In this context, the concept of virtual blending could be explored. A sustained scale up over a relatively short period will require gearing up EU's support and stimulate investments to build a fully-fledged hydrogen ecosystem. By 2030 the EU will aim at completing an open and competitive EU hydrogen market, with unhindered cross-border trade and efficient allocation of hydrogen supply among sectors.
- Phase 3 (from 2030 onwards and towards 2050): renewable hydrogen technologies should reach maturity and be deployed at large scale to reach all hard-to-decarbonise sectors where other alternatives might not be feasible or have higher costs.



Phase 1: 2020-2024

- **6GW** of renewable $H_2$ electrolysers
- 1 million tonnes renewable $H_2$
- Replace **existing** $H_2$ **production**
- Regulation for liquid $H_2$ markets
- Planning $H_2$ infrastructure

Phase 2: 2025-2030

- **40GW** renewable $H_2$ electrolyser
- 10 million tonnes renewable $H_2$
- New applications in steel & transport
- H2 for electricity balancing purposes
- Creation of "Hydrogen Valleys"
- Cross-border logistical infrastructure

Phase 3: 2030-2050

- $H_2$ technologies matured and deployed at large scale in hard to abate sectors.
- Expansion of hydrogen-derived synthetic fuels
- EU-wide infrastructure network
- An open international market

*Figure 8: Hydrogen Strategy – phases* [25]

## 4.2 Hydrogen economy [26]

In order to tailor a supportive policy framework in function of the carbon emission reduction benefits of hydrogen in a transitional phase, and to inform customers, the Commission will work to swiftly introduce, based on impact assessments, EU-wide instruments. This would include:

- a common low-carbon threshold/standard for the promotion of hydrogen production installations, based on their full life-cycle greenhouse gas performance, which could be defined relative to the existing ETS benchmark for hydrogen production.
- a comprehensive terminology and European-wide criteria for the certification of renewable and low-carbon hydrogen, possibly building on the existing ETS monitoring, reporting and verification and the provisions set out in the Renewable Energy Directive. This framework could be based on the full life-cycle greenhouse gas emissions, considering the already existing CertifHy50 methodologies developed by industry initiatives, in consistency with the EU taxonomy for sustainable investments. The specific, complementary functions that Guarantees of Origin (GOs) and sustainability certificates already play in

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[25] European Hydrogen week, 23-27 November 2020, Fuel cells & hydrogen joint undertaking, Sharing best practices of green hydrogen projects in Europe, Bart Biebuyck, 16/09/2020, WebEx

[26] European Commission, «A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

the Renewable Energy Directive can facilitate the most cost-effective production and EU-wide trading.

Building up a hydrogen economy in Europe requires a full value chain approach:

- The production of hydrogen from renewable or low-carbon sources
- The development of infrastructure to supply hydrogen to the end-consumers
- The creation of market demand
- Reduced supply costs – through declining costs for clean production and distribution technologies and affordable costs of renewable energy input, ensuring cost competitiveness with fossil fuels. Off-grid renewable hydrogen production is a further option in this context.
- In addition, it will require a large amount of raw materials. Securing these raw materials should, therefore, be also looked at in the Critical Raw Materials Action Plan, the implementation of the new Circular Economy Action Plan, and EU's trade policy approach to ensure undistorted, fair trade and investments in those raw materials.
- A life-cycle approach is also needed to minimize the negative climate and environmental impacts of the hydrogen sector
- An incentivizing, supportive policy framework needs to enable renewable and, in a transitional period, low-carbon hydrogen to contribute to decarbonization at the lowest possible cost, whilst considering other important aspects, such as industrial competitiveness and its value chain implications for the energy system. The EU already has the basis for a supportive policy-framework notably with the Renewable Energy Directive (described in next chapter) and the Emission Trading System (ETS), while the Next Generation EU, the 2030 Climate Target Plan and the Industrial Policy provide the instruments and financial resources to accelerate our efforts towards a sustainable recovery.

  With the need to scale-up renewable and low-carbon hydrogen before they are cost competitive, support schemes are likely to be required for some time, subject to compliance with competition rules.

  Finally, direct and transparent, market-based support schemes for renewable hydrogen, allocated through competitive tenders, could be envisaged. Market-compatible support should be coordinated within a transparent, efficient and competitive hydrogen and electricity market that provides price signals that reward electrolysers for the services they provide to the energy system (e.g. flexibility services, augmenting renewable production levels, reducing burden from renewable incentives).

Overall, this approach allows for differentiated support for boosting demand and supply, taking into account the type of hydrogen and different starting points of Member States, in line with State aid policy. Investments into renewable and low-carbon hydrogen production installations and technologies, such as electrolysers, can apply for EU funding. Furthermore, carbon contracts for difference for renewable and low-carbon hydrogen could provide initial support for early deployment in various sectors until they have become sufficiently mature and cost-competitive in their own right. For renewable hydrogen, direct market-based support schemes and quotas could also be considered. This should allow to kick-start a hydrogen ecosystem of significant scale throughout the EU in the coming decade and towards full commercial deployment afterwards.

- Finally, further research is needed to support policy making on a number of cross-cutting areas, in particular:
    - to enable improved and harmonized (safety) standards and
    - monitoring and assess social and labor market impacts.
    - reliable methodologies have to be developed for assessing the environmental impacts of hydrogen technologies and their associated value chains, including their full life-cycle greenhouse gas emissions and sustainability
    - securing the supply of critical raw materials in parallel to material reduction, substitution, reuse, and recycling needs a thorough assessment in the light of their future expected increasing deployment, with due account being paid to ensuring security of supply and high levels of sustainability in Europe.
    - coordinated EU research and innovation support is also needed for large-scale high-impact projects across the entire hydrogen value chain, including large scale electrolysers (hundreds of megawatts connected to clean electricity production and supplying renewable hydrogen for

example to industrial areas or green airports and ports (as proposed in the Green Deal Call), that are able to test technology in real life environment.

To address all these challenges the Commission will carry out a set of actions targeting research, innovation, and relevant international cooperation, supporting the energy and climate policy objectives.

## 4.3 Hydrogen economy challenges

However, today renewable and low-carbon hydrogen are not yet cost competitive compared to fossil-based hydrogen [27].

The key limiting factor for the use of hydrogen in industrial applications and transport is often the higher costs, including additional investments into hydrogen-based equipment, storage and bunkering facilities. Furthermore, the potential impact of supply chain risks and market uncertainty are amplified by the tight margins for final industrial products due to international competition [28].

Today, neither renewable hydrogen nor low-carbon hydrogen, notably fossil-based hydrogen with carbon capture, are cost-competitive against fossil-based hydrogen. Estimated costs today for fossil-based hydrogen are around 1.5 €/kg for the EU, highly dependent on natural gas prices, and disregarding the cost of CO2. Estimated costs today for fossil-based hydrogen with carbon capture and storage are around 2 €/kg, and renewable hydrogen 2.5-5.5 €/kg24. Carbon prices in the range of EUR 55-90 per tonne of CO2 would be needed to make fossil-based hydrogen with carbon capture competitive with fossil-based hydrogen today.

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[27] European Commission, «A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

[28] European Commission, «A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

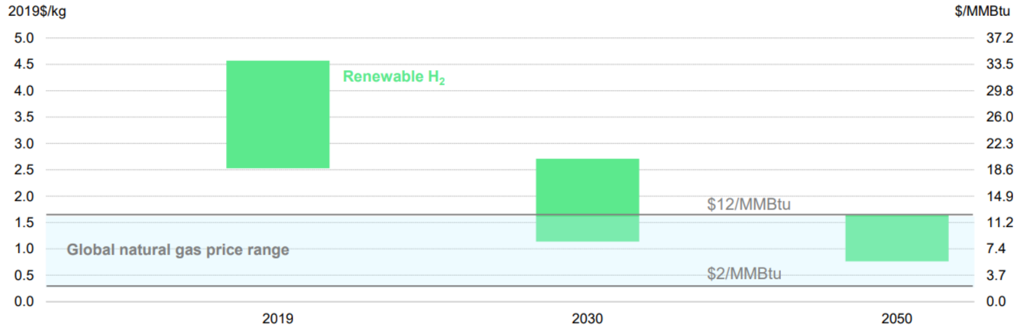

*Figure 9: Renewable hydrogen could compete on price with NG by 2030* [29]

Costs for renewable hydrogen are going down quickly. Electrolyser costs have already been reduced by 60% in the last ten years and are expected to halve in 2030 compared to today with economies of scale. In regions where renewable electricity is cheap, electrolysers are expected to be able to compete with fossil-based hydrogen in 2030. These elements will be key drivers of the progressive development of hydrogen across the EU economy [30]. Rapid upscaling of electrolysers is a key for green hydrogen, as shown below:

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[29] RenPower H2, MENA, Online Conference, 16-17 September 2020, Financing Green Hydrogen Projects in MENA, Antoine Vagneur-Jones.

[30] European Commission, «Questions and answers: A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

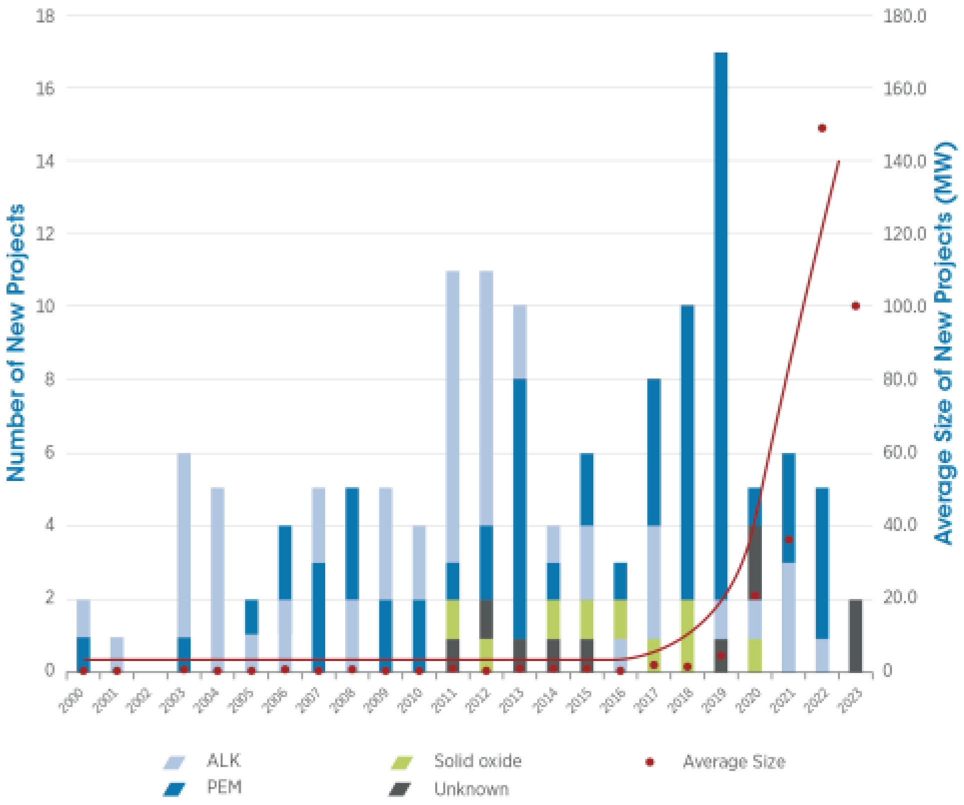

*Figure 10: Rapid upscaling of electrolysers is a key for green hydrogen* [31]

However, deploying hydrogen in Europe faces important challenges that neither the private sector nor Member States can address alone. Driving hydrogen development past the tipping point needs critical mass in investment, an enabling regulatory framework, new lead markets, sustained research and innovation into breakthrough technologies and for bringing new solutions to the market, a large-scale infrastructure network that only the EU and the single market can offer, and cooperation with our third country partners [32].

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[31] RenPower H2, MENA, Online Conference, 16-17 September 2020, IRENA, Hydrogen from renewable power: a global perspective, Emanuele Taibi

[32] European Commission, «A Hydrogen Strategy for a climate neutral Europe», Brussels, 8 July 2020

# CHAPTER 5: HYDROGEN LEGAL FRAMEWORK IN EU AND GREECE

A long list of legislative acts has been found to be (in different ways) relevant to the deployment of hydrogen technologies. Many of the relevant acts impact hydrogen technology deployment indirectly, through its inclusion within the scope of a wider regulatory area (e.g. health and safety, environmental law). These EU legislative acts are often the source of obligations for developers and manufacturers. The extent to which they represent an unreasonable barrier to hydrogen deployment depends on the national implementation of these obligations and differs across the countries covered [33].

Given the increased importance of hydrogen as an energy carrier and as an alternative fuel, a growing body of EU law, references hydrogen directly and specifically regulates certain elements, such as the GHG intensity of hydrogen, technical requirements to be followed by refueling stations, etc. These EU Legislative acts, have a major impact on the deployment of Hydrogen Technology, especially on the use of Hydrogen as a fuel and are rarely the source of an unreasonable barrier to hydrogen deployment [3333].

Nevertheless, as the results of the analysis of legal and administrative processes have shown, many of the barriers to hydrogen deployment are a result of regulatory gaps caused by a lack of harmonization of rules and approaches. (e.g. green hydrogen, certificates of origin, etc.) or by involuntary mismatches between rules imposed at national level (e.g. standards for fuel quality and measurement) rather than high legal and regulatory barriers imposed at EU level [33].

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[33] HyLAW, Deliverable 4.4 EU regulations and directives which impact the deployment of FCH technologies Alexandru Floristean, Hydrogen Europe, February 2019

## 5.1 EU legal instruments

EU secondary legislation is made by the EU institutions. The five EU legal instruments are Regulations, Directives, Decisions, Recommendations and Opinions.

The binding legal instruments that make up the secondary legislation of the EU are Regulations, Directives and Decisions. As set out in Article 288 of the Treaty on the Functioning of the European Union (TFEU):

- Regulations are legal acts that are directly applicable in member states, superseding national laws. They incorporate implementation mechanisms.
- Directives establish objectives that are compulsory to member states but require transposition into national law as they do not include implementation mechanisms. So, a Directive is binding, as to the result to be achieved, upon each Member State to which it is addressed, but leaves to the national authorities the choice of form and methods.
- Decisions can be addressed to both member states and specific entities (e.g. fines for violation of EU competition law). They are directly applicable but usually cover a narrow topic or issue. A Decision is binding in its entirety. A Decision which specifies those to whom it is addressed shall be binding only on them.

Article 288 of the Treaty on the Functioning of the European Union also provides for non-binding legal instruments which have moral and political significance, without being legally binding:

- Recommendations call upon the party to whom they are addressed to behave in a particular way without placing them under any legal obligation.
- Opinions issued by the EU institutions give assessments of situations or developments in the Union or in the individual Member States. They may also prepare the way for subsequent, legally binding acts, or be a prerequisite for the institution of proceedings before the Court of Justice.

The legal forms that will be presented hereinafter are Directives that are compulsory to Member States but require transposition into national laws.

## 5.2 Hydrogen storage

Hydrogen has the highest energy per mass of any fuel, however, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of advanced storage methods that have potential for higher energy density.

Hydrogen storage is a term used for any of several methods for storing hydrogen for later use. It is a key enabling technology for the advancement of hydrogen and fuel cell technologies in applications including stationary power, portable power, and transportation. While large amounts of hydrogen are produced, it is mostly consumed at the site of production, notably for the synthesis of ammonia. Interest in hydrogen storage is driven by the idea that it could be a medium for storing energy, e.g. to compensate for intermittent energy sources.

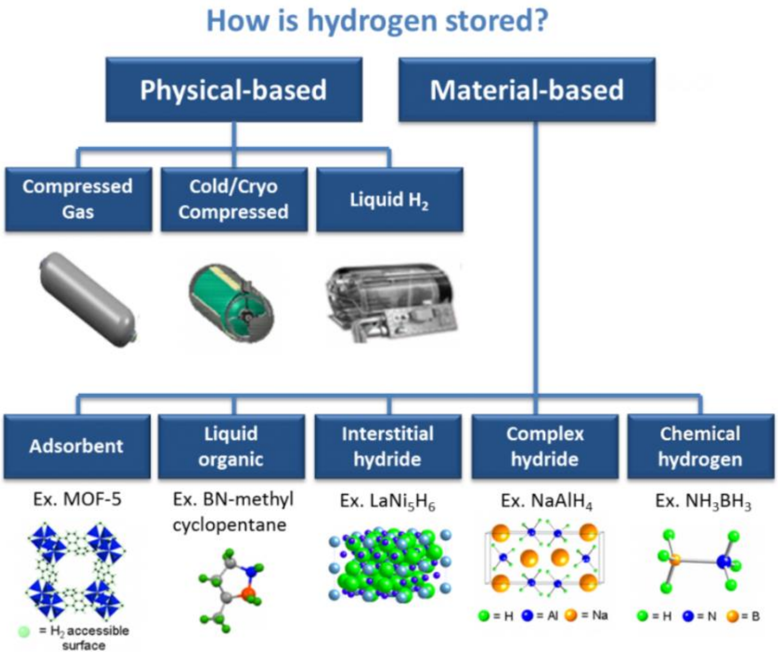

*Figure 11: Hydrogen storage (1)*

Hydrogen storage methods are divided into two groups:

- In natural storage methods, where the hydrogen under certain conditions of pressure and temperature is either in the gas or in the liquid state in suitable tanks (physical-based methods).

- In storage methods using auxiliary materials (material-based methods), where hydrogen is trapped within the structure of an auxiliary material.

Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar [5,000–10,000 psi] tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C.

Hydrogen can also be stored on the surfaces of solids (by adsorption) or in the solids (by absorption).

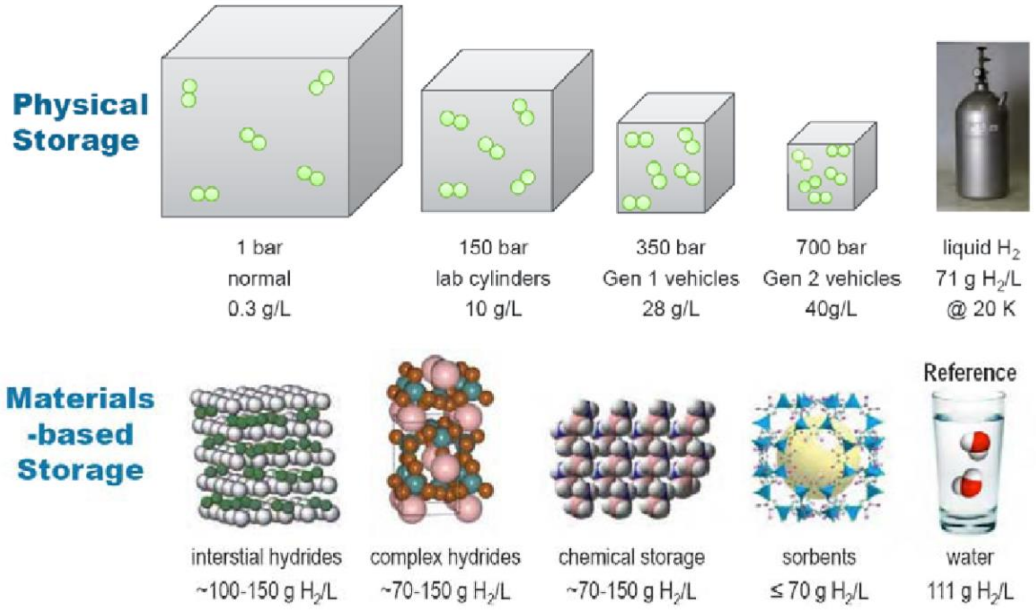

*Figure 12: Hydrogen storage (2)*

The primary challenge is the very low boiling point of H2. It boils around −252.882 °C. Achieving such low temperatures requires significant energy. The most common method of hydrogen storage is compression of the gas phase at high pressure (> 200 bars or 2850 psi).

To fulfill such requirements there are main problems for hydrogen storage such as:

- reducing weight and volume of thermal components is required
- the cost of hydrogen storage systems is too high
- the durability of hydrogen storage systems is inadequate
- hydrogen refueling times are too long

Batteries are not suitable for storing large amounts of electricity over time. For all approaches of hydrogen storage, vessel containment that is resistant to hydrogen permeation and corrosion is required. A major advantage of hydrogen is that it can be produced from (surplus) renewable energies, and unlike electricity, it can also be stored in large amounts for extended periods of time. For that reason, hydrogen produced on an industrial scale could play an important part in the energy transition.

Hydrogen storage is a key technology that allows the advancement of hydrogen and fuel cell technologies and therefore the present legal framework on storage, established by the EU, and adopted by Greece, will be briefly presented.

### 5.2.1 Directive 2012/18/EU - On the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC [34]

First, we have Directive 2012/18/EU on dealing with the risks of major accidents related to dangerous substances and amending and then repealing Directive 96/82/EC (known as the SEVESO Directive). The Directive relates to hydrogen since in Annex I, Part 2, it is established as a hazardous substance, so it falls within the scope, and lists the amount of hydrogen for the application of lower-tier establishments (≥ 5 tonnes) and upper-tier establishments (≥50 tonnes). The Directive covers cases where hazardous substances may be present (eg during storage as in our case) in quantities exceeding certain thresholds.

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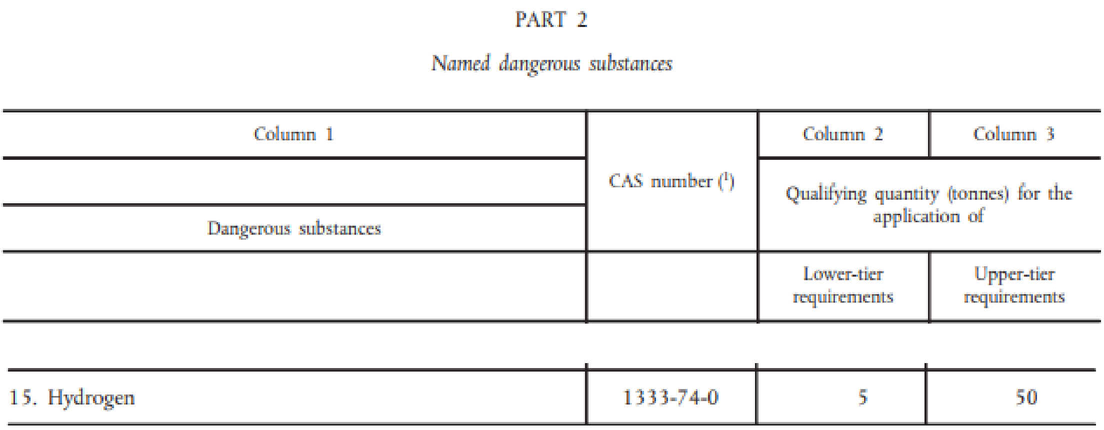
[34] Directive 2012/18/EU – On the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC



PART 2

*Named dangerous substances*

| Column 1 | CAS number (1) | Column 2 | Column 3 |
|---|---|---|---|
| Dangerous substances | | Qualifying quantity (tonnes) for the application of | |
| | | Lower-tier requirements | Upper-tier requirements |
| 15. Hydrogen | 1333-74-0 | 5 | 50 |

*Table 6: Directive 2012/18/EU, Annex I, Part 2, Named dangerous substances*

It lays down:

- the general obligations of the operator for the prevention of major accidents and limitation of their consequences for human health and the environment (Article 5)
- operator's obligation to disclose information (notification) to the competent authority on the physical form and quantity of the dangerous substances, the activity of the installation and the immediate environment of the establishment (Article 7)
- operator's obligation for the implementation of policies and measures for the prevention of major accidents (MAPP) (Article 8)
- operator's obligation for the preparation of safety reports for upper-tier establishments (Article 10, Annex II & III)
- operator's obligation to produce internal emergency plans for upper-tier establishments and to supply the necessary information to the competent authority to draw up external emergency plans (Article 12, Annex IV)
- instructions on Member States on land uses and how to control the location of new installations (that enters into operation or is constructed on or after 1/6/2015), modifications to establishments and new developments such as transport routes, public utility areas and residential areas near the establishment, when the location or works may cause or increase the risk of a major accident (Article 13)

- The obligation to conduct public consultations on specific individual projects that may involve risk of major accidents (Article 15)

Finally, the Directive was incorporated into our domestic law with law 172058/2016 (K.Y.A 172058/2016 (ΦΕΚ 354/Β` 17.2.2016) - Καθορισμός κανόνων, μέτρων και όρων για την αντιμετώπιση κινδύνων από ατυχήματα μεγάλης έκτασης σε εγκαταστάσεις ή μονάδες, λόγω της ύπαρξης επικίνδυνων ουσιών, σε συμμόρφωση με τις διατάξεις της οδηγίας 2012/18/ΕΕ «για την αντιμετώπιση των κινδύνων μεγάλων ατυχημάτων σχετιζομένων με επικίνδυνες ουσίες και για την τροποποίηση και στη συνέχεια την κατάργηση της οδηγίας 96/82/ΕΚ του Συμβουλίου» του Ευρωπαϊκού Κοινοβουλίου και του Συμβουλίου της 4ης Ιουλίου 2012. Αντικατάσταση της υπ’ αριθ. 12044/613/2007 (Β΄376), όπως διορθώθηκε (Β΄2259/2007)).

### 5.2.2 Directive 2014/34/EU - On the harmonization of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres (recast) [35]

The next Directive is 2014/34/EU (known as the ATEX Directive) on the harmonization of the laws of the Member States relating to devices and protection systems intended for use in explosive atmospheres.

The Directive:

- sets out the essential health and safety requirements relating to the design and construction of equipment and protective systems intended for use in potentially explosive atmospheres, that must be applied before the products can be placed on the EU market and is important for the design of hydrogen production plants and storage facilities (Article 4, Annex II)

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[35] Directive 2014/34/EU - On the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres (recast)

- describes the rules and regulations for all actors in the production chain:
    - authorities
    - conformity assessment bodies (Article 21-31)
    - notifying authorities (Article 18-20)
    - economic operators (Article 11) such as:
        - manufacturers (Article 6)
        - authorized representatives (Article 7)
        - importers (Article 8) and
        - distributors (Article 9)

  to ensure that only safe equipment for use in potentially explosive atmospheres is sold and applied.
- contains conformity assessment procedures (Article 13, Annex III, IV, V, VI, VII, VIII, IX), EU declaration of conformity (Article 14, Annex X), General principles (Article 15) and rules of the CE marking (Article 16)
- obliges employers to classify areas where hazardous explosive atmospheres may occur into zones. The classification given to a particular zone, and its size and location, depends on the likelihood of an explosive atmosphere occurring and its persistence if it does.

This Directive was internalized with the Greek law 52019 / DTBN 1152/2016 (Υ.Α. Οικ. 52019/ΔΤΒΝ 1152/2016 (ΦΕΚ 1426/Β` 20.5.2016) - Προσαρμογή της ελληνικής νομοθεσίας προς τις διατάξεις της Οδηγίας 2014/34/ΕΕ του Ευρωπαϊκού Κοινοβουλίου και του Συμβουλίου της 26ης Φεβρουαρίου 2014 για την εναρμόνιση των νομοθεσιών των κρατών μελών σχετικά με τις συσκευές και τα συστήματα προστασίας που προορίζονται για χρήση σε εκρήξιμες ατμόσφαιρες (αναδιατύπωση)).

### 5.2.3 Directive 2014/68/EU - On the harmonization of the laws of the Member States relating to the making available on the market of pressure equipment (recast) [36]

There is also Directive 2014/68/EU on the harmonization of the laws of the Member States relating to the availability of pressure equipment on the market (known as the Pressure Equipment Directive PED). This applies to the design, manufacture and conformity assessment of pressure equipment and assemblies subject to a maximum allowable pressure greater than 0.5 bar.

The objective of this Directive is:

- to ensure that pressure equipment or assemblies on the market fulfil the requirements providing a high level of protection of health and safety of persons and protection of domestic animals or property

Directive:

- sets out all technical requirements (Article 4, Annex I) and classification (Article 13) according to an ascending level of hazard, depending on pressure, volume or nominal size, the fluid group and state of aggregation ("fluids" means gases, liquids and vapors in pure phase as well as mixtures thereof. Fluids may contain a suspension of solids)
- describes the rules and regulations for all actors in the production chain:
  - authorities
  - conformity assessment bodies (Article 24, 26-30, 32-36)
  - notifying authorities (Article 21-24)
  - user inspectorates (Article 25, 33-36)
  - economic operators (Chapter 2) such as:
    - manufacturers (Article 6)
    - authorized representatives (Article 7)
    - importers (Article 8) and

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[36] Directive 2014/68/EU - On the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment (recast)

    - distributors (Article 9)
- contains conformity assessment procedures (Article 14, Annex III), EU declaration of conformity (Article 17, Annex IV), General principles (Article 18) and rules of the CE marking (Article 19)

Hydrogen is a Group 1 fluid (Article 13). Group 1 consists of dangerous fluids (flammable, toxic and/or oxidizing). Therefore, much of the hydrogen production, storage and distribution equipment must meet the technical requirements described in the Pressure Equipment Directive (PED).

This Directive has been incorporated by our national law with the law 74124/ DTBN, 1431/2016 (Υ.Α. οικ. 74124/ΔΤΒΝ 1431/2016 (ΦΕΚ 2278/Β` 22.7.2016) - Προσαρμογή της ελληνικής νομοθεσίας προς την Οδηγία 2014/68/ΕΕ του Ευρωπαϊκού Κοινοβουλίου και του Συμβουλίου της 15ης Μαΐου 2014 για την εναρμόνιση των νομοθεσιών των κρατών μελών σχετικά με τη διαθεσιμότητα του εξοπλισμού υπό πίεση στην αγορά (αναδιατύπωση)).

### 5.2.4 Directive 2001/42/EC - On the assessment of the effects of certain plans and programs on the environment (SEA) [37]

The objective of this Directive is to provide for a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and programs with a view to promoting sustainable development, by ensuring that, in accordance with this Directive, an environmental assessment is carried out of certain plans and programs which are likely to have significant effects on the environment.

The Directives define a strategic environmental impact assessment procedure, which is summarized as follows:

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[37] Directive 2001/42/EC - On the assessment of the effects of certain plans and programmes on the environment (SEA)

- the competent authorities shall be consulted when deciding on the scope and level of detail of the information which must be included in the environmental report (Article 5)
- The draft plan or program and the environmental report prepared shall be made available to the authorities, the public (Article 6) and affected Member State (Article 7)
- The authorities and the public referred shall be given an opportunity within appropriate time frames to express their opinion on the draft plan or program and the environmental report before the adoption of the plan or program (Article 6)
- Member States shall ensure that, when a plan or program is adopted, the authorities, the public and any affected Member State are informed (Article 9)
- Member States shall monitor the environmental effects of the implementation of plans and programs and undertake remedial action, if any (Article 10)

This Directive has been incorporated by our national law with law 107017/2006 (ΦΕΚ 1225/Β΄, 6/9/2006, Αριθμ. ΥΠΕΧΩΔΕ/ΕΥΠΕ/οικ. 107017/2006 - Εκτίμηση των περιβαλλοντικών επιπτώσεων ορισμένων σχεδίων και προγραμμάτων, σε συμμόρφωση με τις διατάξεις της οδηγίας 2001/42//ΕΚ «σχετικά με την εκτίμηση των περιβαλλοντικών επιπτώσεων ορισμένων σχεδίων και προγραμμάτων» του Ευρωπαϊκού Κοινοβουλίου και του Συμβουλίου της 27ης Ιουνίου 2001).

### 5.2.5 Directive 2014/52/EU - Amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (EIA) [38]

The objective of this Directive (known as EIA Directive) is namely to ensure a high level of protection of the environment and of human health, through the establishment of minimum requirements for the environmental impact assessment of projects.

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[38] Directive 2014/52/EU - Amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (EIA)

Production and Storage of Hydrogen falls within the projects listed in EIA Directive, Annex II, 6a (Chemical Industry - Treatment of intermediate products and **production of chemicals**) and 6c (Chemical Industry - **Storage facilities for** petroleum, petrochemical and **chemical product**), for which Member States shall determine whether the project shall be made subject to an assessment or not (screening procedure). In some EU countries, storage of 5 tons of hydrogen or more falls within the scope of the Directives.

The Directive sets out:

- the selection criteria taken into account in order to determine which projects are to be subject to environmental assessment (Directive 2011/92/EU, Annex III) – screening procedure
- that the competent authority should, where requested by the developer, issue an opinion on the scope and level of detail of the environmental information to be submitted in the form of an environmental impact assessment report (‘scoping’) (30)
- that data and information included by the developer in the environmental impact assessment report should be in accordance with Annex IV of Directive 2011/92/EU (32)
- that the environmental authorities and the public (Article 6) as well as affected Member States must be informed and consulted (Article 7)
- that the competent authority decides, taken into consideration the results of consultations (Article 8)
- that the public is informed of the decision afterwards and can challenge the decision before the courts (Article 11)

This Directive has been incorporated by our national law with:

- law 5688/12-3-2018 (fully integrated into Greek legislation) (KYA Αριθμ.οικ.5688/12-3-2018, (ΦΕΚ 988/Β/21-3-2018) - Τροποποίηση των παραρτημάτων του ν. 4014/2011 (Α΄ 209), σύμφωνα με το άρθρο 36Α του νόμου αυτού, σε συμμόρφωση με την Οδηγία 2014/52/ΕΕ «για την τροποποίηση της οδηγίας 2011/92/ΕΕ σχετικά με την εκτίμηση των επιπτώσεων ορισμένων σχεδίων δημόσιων και ιδιωτικών έργων στο περιβάλλον» του Ευρωπαϊκού Κοινοβουλίου και του Συμβουλίου της 16ης Απριλίου 2014).

- law 4519/2018 (ΚΥΑ Αριθμ. οικ. 4519/2018 (ΦΕΚ Α 25 - 20.02.2018) Φορείς Διαχείρισης Προστατευόμενων Περιοχών και άλλες διατάξεις).
- law 1915/24-01-2018 (partially incorporation into Greek law) (ΚΥΑ Αριθμ. οικ. 1915/24-01-2018, (ΦΕΚ 304/Β/2-2-2018) - Τροποποίηση των υπ’ αριθμ. 48963/2012 (Β΄ 2703) κοινής υπουργικής απόφασης, υπ’ αριθμ. 167563/2013 (Β΄ 964) κοινής υπουργικής απόφασης και υπ’ αριθμ. 170225/2014 (Β΄ 135) υπουργικής απόφασης, που έχουν εκδοθεί κατ΄ εξουσιοδότηση του ν. 4014/2011 (Α΄ 209), σε συμμόρφωση με την Οδηγία 2014/52/ΕΕ «για την τροποποίηση της οδηγίας 2011/92/ΕΕ σχετικά με την εκτίμηση των επιπτώσεων ορισμένων σχεδίων δημόσιων και ιδιωτικών έργων στο περιβάλλον» του Ευρωπαϊκού Κοινοβουλίου και του Συμβουλίου της 16ης Απριλίου 2014)

### 5.2.6 Conclusion

In conclusion, we can state that the environmental, safety and health requirements contained in the above legislation are general, having a wide application and not specifically for hydrogen. Hydrogen storage is included, but non-adapted rules or lack thereof increase the cost for those interested in developing hydrogen infrastructure.

## 5.3 Hydrogen Refueling Stations

In this paragraph there will be a brief presentation of the legislation concerning the Hydrogen Refueling Stations for Road Transport (Hydrogen Refueling Stations).

These refueling points can be available in the following designs:

- of different size (e.g. depending on the amount of hydrogen stored)
- with or without on-site hydrogen production
- with different storage and pressure conditions (eg 350 or 700 bars)
- with the possibility that hydrogen can coexist with other fuels in the same space or not

- with the possibility that hydrogen can be supplied via a pipeline or transported to the station by trailers
- with the possibility that hydrogen can be dispensed in gaseous or liquid form, etc.

As a result of the above, a large number of rules can be applied in the design, licensing, construction and operation of hydrogen refueling points. The Directives that will be described in the following paragraphs are addressing issues related either to the Hydrogen Refueling Station or to the use of Hydrogen as fuel.

### Fuel cell vehicles [39]

Fuel cell electric vehicles, like battery electric vehicles, use electricity to power an electric motor. The difference is that the electricity is produced by a fuel cell powered by compressed hydrogen gas instead of relying on a battery. These vehicles have a fuel tank onboard which has to be filled in a hydrogen charging station. FCEVs do not have harmful tailpipe emissions – they only emit water and heat – and therefore are an option to achieve zero emissions in the freight transport sector, as long as they use green hydrogen.

FCEVs are still at a very early stage of deployment and comprise a negligibly small part of the global road transport fleet. For wider uptake, the high cost of fuel cells needs to fall and a hydrogen charging network needs to be in place. Interest in FCEVs for passenger vehicles had grown over the last few years but now seems to be declining. Recently, a handful of automakers, such as Daimler and Honda, announced that they would stop developing hydrogen fuel cell passenger cars due to their high manufacturing costs and the improving performance of battery electric vehicles. However, interest in FCEVs for heavy-duty vehicles may be growing.

FCEVs may allow for higher ranges across all truck classes compared to current battery electric vehicle technologies. For example, the Nikola One fuel cell has a maximum range of over 1.100 kilometres for a Class 8 tractor-trailer application. Anheuser-Busch recently ordered 800 hydrogen trucks from Nikola Motors which will

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[39] IRENA, Reaching zero with renewables, Eliminating CO2 emissions from industry and transport in line with the 1,5oC climate goal

be serviced by 28 dedicated hydrogen refuelling stations, with a plan to increase this number to 700 stations across the US and Canada by 2028.

### 5.3.1 Directive 2014/94/EU - On the deployment of alternative fuels infrastructure (AFID) [40]

Directive on the deployment of alternative fuels infrastructure (Directive 2014/94/EU) (known as AFID) is the key piece of European legislation on hydrogen refueling points for road transport, which sets out:

- «minimum requirements for the building-up of alternative fuels infrastructure, including … refueling points for … hydrogen, to be implemented by means of Member States' national policy frameworks, as well as
- common technical specifications for such … refueling points, and
- user information requirements» (Article 1)

«This Directive establishes a common framework of measures for the deployment of alternative fuels infrastructure in the Union in order to minimize dependence on oil and to mitigate the environmental impact of transport» (Article 1)

It is important to emphasize that «EU Member States that will decide to include in their national policy framework, hydrogen refueling points accessible to the public, shall ensure that, by 31 December 2025, an appropriate number of such points are available, to ensure the circulation of hydrogen-powered motor vehicles, including fuel cell vehicles, within networks determined by those Member States, including, where appropriate, cross-border links» (Article 5)

According to the Directive, «“Alternative fuels” are fuels or power sources which serve, at least partly, as a substitute for fossil oils sources in energy supply to transport and which have the potential to contribute to its decarbonization and enhance the environmental performance of transport sector. They include, inter alia:

- electricity

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[40] Directive 2014/94/EU - On the deployment of alternative fuels infrastructure (AFID)

- hydrogen
- biofuels as defined in point (i) of Article 2 of Directive 2009/28/EC
- synthetic and paraffinic fuels
- natural gas, including biomethane in gaseous form (CNG) and liquefied form (LNG) and
- liquefied petroleum gas (LPG)» (Article 2)

«Based on the national policy frameworks, the Commission shall publish and regularly update information on the national targets and the objectives submitted by each Member State regarding hydrogen refueling points accessible to the public» (Article 3).

This Directive has been incorporated by our national law with law N. 4439/2016 (N. 4439/2016 (ΦΕΚ 222/Α` 30.11.2016) - Ενσωμάτωση στην ελληνική νομοθεσία της Οδηγίας 2014/94/ΕΕ του Ευρωπαϊκού Κοινοβουλίου και του Συμβουλίου της 22ας Οκτωβρίου 2014 για την ανάπτυξη υποδομών εναλλακτικών καυσίμων, απλοποίηση διαδικασίας αδειοδότησης και άλλες διατάξεις πρατηρίων παροχής καυσίμων και ενέργειας και λοιπές διατάξεις).

«Where appropriate, and in particular for … hydrogen, when fuel prices are displayed at a fuel station, a comparison between the relevant unit prices shall be displayed for information purposes. The display of this information shall not mislead or confuse the user» (Article 7)

Annex II contains technical specifications for hydrogen refueling points for motor vehicles and additionally lays down that:

- Outdoor hydrogen refueling points dispensing gaseous hydrogen used as fuel on board motor vehicles shall comply with the technical specifications of the ISO/TS 20100 Gaseous Hydrogen Fueling specification.
- The hydrogen purity dispensed by hydrogen refueling points shall comply with the technical specifications included in the ISO 14687-2 standard.
- Hydrogen refueling points shall employ fueling algorithms and equipment complying with the ISO/TS 20100 Gaseous Hydrogen Fueling specification.
  - Connectors for motor vehicles for the refueling of gaseous hydrogen shall comply with the ISO 17268 gaseous hydrogen motor vehicle refueling connection devices standard» (Annex II)

### 5.3.2 Directive (EU) 2018/2001 - On the promotion of the use of energy from renewable sources (recast) (RED II) (replacing Directive 2009/28/EC) [41] [42] [43]

Until the adoption of the recast Renewable Energy Directive (RED II) the most relevant EU legislative act for the use of Hydrogen as a fuel was the Alternative Fuels Infrastructure Directive (AFID). While, in this Directive, hydrogen is not explicitly mentioned as ‘renewable energy’ in its own right in RED Article 2(1), ‘green’ hydrogen is included indirectly in the scope of RED. This becomes clear from the second sentence of Article 7(1), concerned with calculating the share of energy from renewable sources: ‘hydrogen from renewable sources shall be considered only once for the purposes of calculating the share of gross final consumption of energy from renewable sources’. RED Recital 59 acknowledges indirectly that the term ‘renewable gas’ encompasses hydrogen from renewable energy sources (*…It would also enable the creation of guarantees of origin for other renewable gas such as hydrogen”*)

The Recast Renewable Energy Directive (Directive (EU) 2018/2001 (RED II) on the promotion of the use of energy from renewable sources (RED) has a strong, impact on hydrogen fuel deployment as:

- «establishes a strong common framework for the promotion of energy from renewable sources. It sets a binding Union target for the overall share of energy from renewable sources in the Union's gross final consumption of energy in 2030. It also lays down rules on financial support for electricity from renewable sources, on self-consumption of such electricity, on the use of energy from renewable sources in the heating and cooling sector and in the transport sector, on regional cooperation between Member States, and between Member States and third countries, on guarantees of origin, on administrative procedures and on

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[41] Directive (EU) 2018/2001 - On the promotion of the use of energy from renewable sources (recast) (RED II).

[42] European Commission, Renewable Energy Directive, https://ec.europa.eu/energy /topics/renewable-energy/directive-targets-and-rules/renewable-energy-directive_en

[43] Ruven Fleming (2021) Clean or renewable – hydrogen and power-to-gas in EU energy law, Journal of Energy & Natural Resources Law, 39:1, 43-63, DOI: 10.1080/02646811.2020.1795382

information and training. It also establishes sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids and biomass fuels» (Article 1)

- it sets a mandatory collective minimum target of 32% for 2030 for the overall share of energy from renewable sources in gross final consumption of energy for all Member State (Article 3)
- it sets mandatory national targets for the overall share of energy from renewable sources (Article 3)
- it sets a mandatory obligation on fuel suppliers to ensure a minimum 14% share of renewable energy content in fuels supplied for the transport sector by 2030. For the calculation of the 14% minimum share, Member States shall take into account renewable liquid and gaseous transport fuels of non-biological origin (i.e. renewable hydrogen) also when they are used as intermediate products for the production of conventional fuels (Article 25)
- it lays down a legally binding definition of renewable liquid and gaseous transport fuels of non-biological origin (which applies to Hydrogen) (Article 2) for the purpose of calculating the targets and incentivizes the use of renewable hydrogen as a fuel or as an intermediate product over other potential renewable fuels (Article 27)
- it requires that the greenhouse gas emissions savings from the use of renewable liquid and gaseous transport fuels of non- biological origin (which applies to Hydrogen) shall be at least 70 % from 1 January 2021 (Article 25), the implication of which requires further clarification in the context of implementing acts
- the share of renewable electricity (which in our interpretation includes hydrogen produced from renewable electricity) shall be considered to be four times its energy content when supplied to road vehicles for the purposes of demonstrating compliance with the 14% encouraging these types of fuels over other types of renewable fuels (e.g. bio fuels and advanced bio-fuels) (Article 27)
- Guarantees of Origin shall now be issued for renewable gases, including ‘green’ hydrogen (Recital 59 and Article 19, 7) b) ii)). According to Article 19(1), each member state must be able to guarantee the origin of energy from renewable sources.

The implications of this provision on the Petro-chemical industry are massive, as they encourage upstream changes which will partially decarbonize the production of conventional fuels.

The transposition into Greek national law of Directive (EU) 2018/2001 is one of the outstanding issues that Greek Ministry of Energy wants to close immediately. For this purpose, a working group has been set up, which is responsible for the task of harmonizing this Directive with national law. The Working Group will cooperate for this purpose with a contractor, who will undertake the drafting of the relevant legislative and regulatory texts, with any modifications and additions to the existing framework required. The transposition has not yet been completed.

The Commission proposed a revision of the directive in July 2021, as part of the package to deliver on the European Green Deal. The proposal raises the ambition of the existing legislation to align it with EU's increased climate ambition. It also seeks to introduce new measures to complement the already existing building blocks established by the 2009 and 2018 directives, to ensure that all potentials for the development of renewable energy are optimally exploited – which is the necessary condition to achieve the EU's objective of climate neutrality by 2050.

The proposed revision aims to ensure that renewable energy fully contributes to achieving a higher EU climate ambition for 2030, in line with the 2030 Climate Target Plan. It seeks to convert into EU law some of the concepts outlined in the energy system integration and hydrogen strategies, published in 2020. The 2 strategies outlined ways of creating an integrated energy system, based on renewable energy and fit for climate neutrality, and turning hydrogen into a viable solution to help reach the objectives of the European Green Deal.

In line with the EU Climate Law, the targets and measures set in the revised directive should be ambitious enough to reduce greenhouse gas emissions by at least 55% in 2030. This includes raising the overall renewables target (proposed to be increased to 40%), but also strengthened measures for transport or heating and cooling. The Commission is also aiming at a more energy efficient and circular energy system that facilitates renewables-based electrification and promotes the use of renewable and low-carbon fuels, including hydrogen, in sectors where electrification is not yet a feasible option, such as transport.

The revision process:

- On 21 July 2021, the Commission presented a proposal for a revised directive, as part of the package to deliver on the European Green Deal.
- The proposed revision of the directive is now being considered by the Council and the European Parliament. The adoption is expected by end of 2022.
- As a first step in the revision process, the Commission published a roadmap in August 2020. The feedback received from stakeholders and the public on the contributed to the Commission’s preparatory work for the review.
- A public consultation was launched in 2020 and a short summary was published in March 2021. In addition, 2 stakeholder meetings were organized in December 2020 and in March 2021 to gather input from stakeholders.

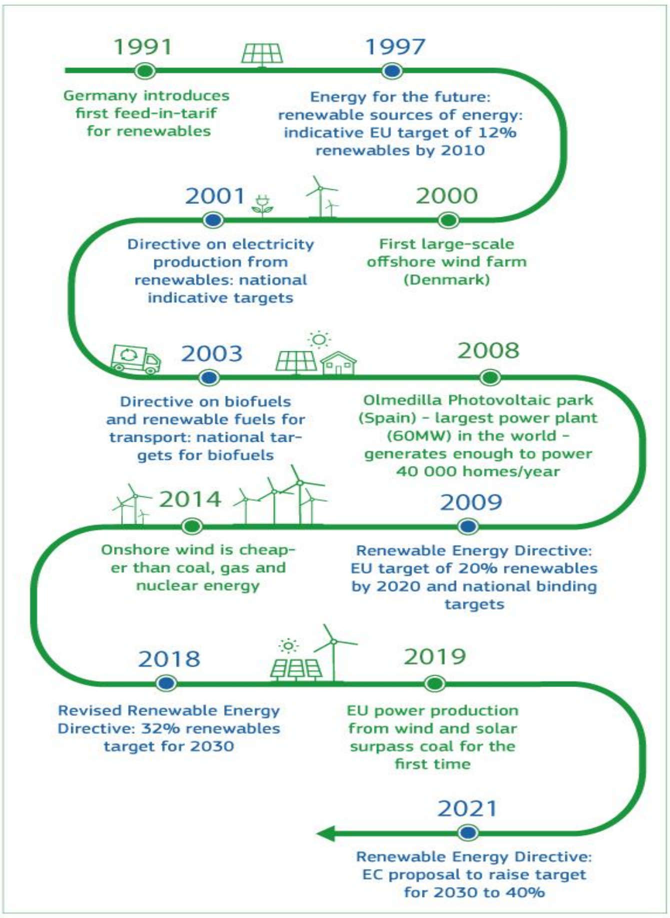

*Figure 13: Timeline for renewable energy in the EU*

### 5.3.3 Directive (EU) 2015/1513 - Amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources [44]

Directive 2015/1513/EU amending:

- Directive 98/70/EC on the quality of petrol and diesel fuels and
- Directive 2009/28/EC on the promotion of the use of energy from renewable sources

includes renewable hydrogen in the list of fuels from renewable sources by giving a legally binding definition of renewable liquid and gaseous transport fuels of non-biological origin (which applies to Hydrogen):

«“renewable liquid and gaseous transport fuels of non-biological origin” means liquid or gaseous fuels other than biofuels whose energy content comes from renewable energy sources other than biomass, and which are used in transport»

### 5.3.4 Directive 2015/652 - Laying down calculation methods and reporting requirements pursuant to Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels [45]

This Directive establishes the Method for the calculation and reporting of the life cycle greenhouse gas intensity of fuels and energy by suppliers. More particular it defines:

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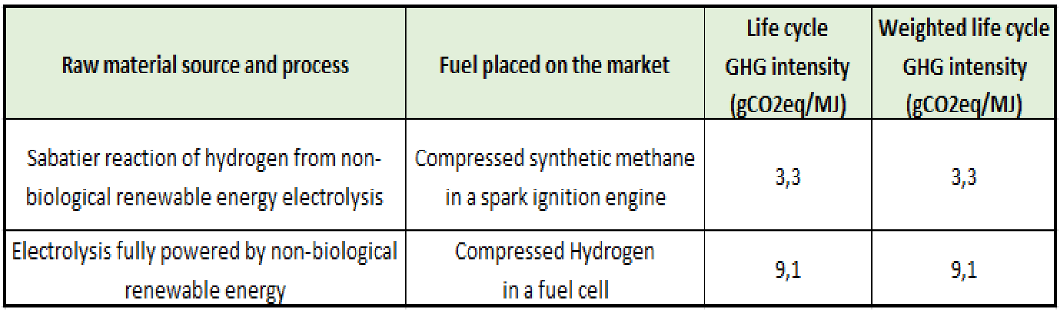
[44] Directive (EU) 2015/1513 - Amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources

[45] Directive 2015/652 - laying down calculation methods and reporting requirements pursuant to Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels

- the efficiency factor (adjustment factor for powertrain efficiencies) of the hydrogen fuel cell electric powertrain to be 0,4 (Annex I, Part 1).
- the average life cycle greenhouse gas intensity default values for fuels other than biofuels and electricity, including renewable hydrogen which has the lowest GHG intensity of the fuels considered (Annex I, Part 2).



| Raw material source and process | Fuel placed on the market | Life cycle GHG intensity (gCO2eq/MJ) | Weighted life cycle GHG intensity (gCO2eq/MJ) |
|---|---|---|---|
| Sabatier reaction of hydrogen from non-biological renewable energy electrolysis | Compressed synthetic methane in a spark ignition engine | 3,3 | 3,3 |
| Electrolysis fully powered by non-biological renewable energy | Compressed Hydrogen in a fuel cell | 9,1 | 9,1 |

*Table 7: Average life cycle greenhouse gas intensity default values for fuels other than biofuels and electricity*

### 5.3.5 Directive 2009/30/EC - Amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC [46]

Article 7a of Directive 2009/30/EC states that Member States shall require suppliers to reduce as gradually as possible life cycle greenhouse gas emissions per unit of energy from fuel and energy supplied by 6 % by 31 December 2020 and aim for an additional

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[46] Directive 2009/30/EC - Amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC

2% reduction through the use of any technology capable of reducing life cycle greenhouse gas emissions per unit of energy from fuel or energy supplied.

So, in this directive there is no direct reference to hydrogen. It, however, indirectly affects the use of fuels which are defined by low greenhouse emissions, with hydrogen being one of that.

### 5.3.6 Directive 2012/18/EU - On the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC [47]

This Directive is also applicable for Hydrogen storage and has been thoroughly presented in paragraph 4.2.1 above.

### 5.3.7 Directive 2014/34/EU - On the harmonization of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres (recast) [48]

This Directive is also applicable for Hydrogen storage and has been thoroughly presented in paragraph 4.2.2 above.

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[47] Directive 2012/18/EU – On the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC

[48] Directive 2014/34/EU - On the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres (recast)

### 5.3.8 Directive 2014/68/EU - On the harmonization of the laws of the Member States relating to the making available on the market of pressure equipment (recast) [49]

This Directive is also applicable for Hydrogen storage and has been thoroughly presented in paragraph 4.2.3 above.

### 5.3.9 Directive 2001/42/EC - On the assessment of the effects of certain plans and programs on the environment (SEA) [50]

This Directive is also applicable for Hydrogen storage and has been thoroughly presented in paragraph 4.2.4 above.

### 5.3.10 Directive 2014/52/EU - Amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (EIA) [51]

This Directive is also applicable for Hydrogen storage and has been thoroughly presented in paragraph 4.2.5 above.

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[49] Directive 2014/68/EU - On the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment (recast)

[50] Directive 2001/42/EC - On the assessment of the effects of certain plans and programmes on the environment (SEA)

[51] Directive 2014/52/EU - Amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (EIA)

### 5.3.11 Conclusion [52]

Directives mentioned in part «4.1 Hydrogen storage», are also applicable in Hydrogen Refueling Stations, since they are relevant for the production, storage of hydrogen as well as the development of hydrogen supply infrastructure.

The Renewable Energy Directive (EU) 2018/2001 lays down a legally binding definition of renewable liquid and gaseous transport fuels of non-biological origin. This definition also includes hydrogen for the purposes of calculating compliance with the targets set out in the directive (32 % share of renewable energy in EU gross final consumption and 14 % renewables share of transport energy by 2030).

The Alternative Fuels Infrastructure Directive 2014/94/EU establishes a common framework and sets out minimum requirements for the roll-out of alternative fuels infrastructure in the Member States, including refueling points for hydrogen.

Both directives are to be revised by the second quarter of 2021, under the Fit for 55 package, with a view to increasing their climate action ambition.

The Fuel Quality Directive 98/70/EC indirectly promotes the use of hydrogen, by requiring fuel suppliers to reduce the life cycle GHG emissions per unit of energy by 6 % by 31 December 2020. It is complemented by Council Directive (EU) 2015/652 (laying down the calculation methods and reporting requirements), which sets the efficiency factor of the hydrogen fuel cell electric powertrain to 40 % and fixes the GHG intensity of clean and fossil-based hydrogen and of hydrogen-derived methane.

In addition, the HyLaw project identified more than 50 EU legislative acts in wider regulatory areas that impact hydrogen technology development indirectly and would need to be considered, among them health and safety, environment, labour, and transport.

An initial conclusion is that at European level there is a legal framework that refers directly or indirectly to hydrogen technology (in our case hydrogen refueling stations),

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[52] European Parliament, Briefing towards climate neutrality, EU hydrogen policy, Hydrogen as an energy carrier for climate-neutral economy

but there is still much room for improvement in its development. Key improvements at the forthcoming revision of «On the deployment of alternative fuels infrastructure» Directive (AFID):

- to compulsorily include hydrogen as such a fuel
- to have similar infrastructure development requirements to compressed natural gas (CNG) infrastructure and
- to reduce the distance between hydrogen refueling stations from 300 km to 150 km, to be equal to the current distance between compressed natural gas (CNG) stations.

Regarding EU Member States, from Table 8, it clearly appears that the most acknowledged pathway, from a legal standpoint, is the use of hydrogen as fuel (HtF-H2) for fuel-cell vehicles, since it benefits from general incentives for electric or low-emission vehicles. Specific regulations seem to be lacking for several pathways. Incentives begin appearing for the industrial sector, which is recently gaining momentum. Compared to other countries, the Netherlands (NL) seem to be implementing a global legal framework, encompassing the variety of hydrogen applications. France seems to be on the same pathway, but industry uses do not appear in the agenda of most examined countries. The most frequently considered pathway, from a legal standpoint, is using hydrogen for mobility applications. Only a few countries are implementing legal frameworks for diverse hydrogen applications [53].

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[53] International Journal of Hydrogen Energy, Incentives and legal barriers for Power-to-Hydrogen pathways: An international snapshot, May 2019

| Country | | BE | FR | DE | IT | JP | NZ | NO | ES | NL | UK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **PtH** | | | 🟧 | | | | | 🟩 | | 🟩 | |
| **HtP** | | | | | | | | | | 🟩 | |
| **HtF** | *HtF-H2* | 🟩 | 🟩 | 🟩 | 🟢 | 🟩 | 🟢 | 🟩 | 🟩 | 🟢 | 🟩 |
| | *HtF-S* | | | | | | | | | | |
| | *HtF-G* | | | | | | | | | | |
| **HtG** | *HtG-H2* | 🟢 | 🟩 | 🟩 | 🟢 | 🟥 | | | 🟩 | 🟧 | 🟧 |
| | *HtG-M* | 🟢 | 🟢 | 🟢 | | | | | | 🟢 | |
| **HtI** | | | 🟢 | | | | | | | 🟢 | |
| **HtCh** | | | | | | | | | | | |
| **HtQ** | | | | | | | | | | | |

| | |
|---|---|
| favourable context | 🟩 |
| somehow favourable | 🟢 |
| somehow difficult | 🟧 |
| difficult context | 🟥 |
| no information | |

| | |
|---|---|
| PtH | Power-to-Hydrogen |
| HtP | Hydrogen-to-Power |
| HtG-H2 | Hydrogen-to-Gas (feed-in H2) |
| HtG-M | Hydrogen-to-Gas (feed-in of synthetic methane) |
| HtF-H2 | Hydrogen-to-Fuel (Hydrogen) |
| HtF-S | Hydrogen-to-Fuel (liquid synfuels) |
| HtF-G | Hydrogen-to-Fuel (gaseous synfuels) |
| HtI | Hydrogen-to-Industry |
| HtQ | Hydrogen-to-Heat |
| HtCh | Hydrogen-to-Chemicals |

*Table 8: Legal framework according to the pathways*

# CHAPTER 6: FIVE GREEK HYDROGEN PROJECTS (IPCEI) [54] [55]

EU recognises the importance of promoting cross-border collaboration and of working on large-scale joint investment projects in order to support the development and deployment of hydrogen technologies and systems, particularly in hard-to-abate sectors where hydrogen and its derivatives are either the only available or the most cost-efficient decarbonisation solution, and of fostering a liquid, sustainable and contestable European hydrogen market in the near future as well as supporting export industries.

The joint projects shall include sectors along the whole hydrogen value chain, notably:

(i) the safe and sustainable low-carbon production of hydrogen, where emphasis should be given to hydrogen from renewable sources, and its derivatives
(ii) equipment manufacturing (incl. electrolysers and equipment for heavy-duty mobility, such as light commercial vehicles, buses, trucks, hard-to-electrify railways, shipping or aviation)
(iii) solutions for hydrogen storage, transmission and distribution (incl. refuelling stations along roads, rails and ports), and
(iv) industrial applications of hydrogen (incl. the decarbonisation of industrial facilities).

Projects should encompass research, development, innovation activities, first industrial deployment and the large-scale roll-out and broad implementation of related installations, factories and networks, based on a clustered approach where possible, in order to achieve an initial range of significant hydrogen-based GHG-emission reductions, thereby being of great importance for the environment, energy, and transport strategy goals of the Union.

To this end, EU strives to promote the realisation of “Important Projects of Common European Interest on Hydrogen Technologies and Systems” (IPCEI on Hydrogen), as

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[54] Minister of Development and Investments, mindev.gov.gr
[55] Manifesto for the development of a European “Hydrogen Technologies and Systems” value chain, eu2020.de

recommended in the report of the Strategic Forum for IPCEIs on the 6 key strategic value chains, and chiefly on the “Hydrogen Technologies and Systems” key value chain. The objective of the IPCEI on Hydrogen is:

- to guarantee Europe’s technological leadership
- to allow European companies to take the lead on the emerging markets for hydrogen, and to build a European framework for the emergence of a hydrogen value chain.
- a significant contribution to the reduction of greenhouse gas emissions and facilitating the integration of renewable sources in the participating Member States in accordance with their National Energy and Climate Plans.

Five ground-breaking hydrogen projects have been unveiled for Greece. The projects, dubbed Blue Med, Green HIPo, White Dragon, H2CAT Tanks, H2CEM, were all approved by the Ministers of Development and Investments and the Minister of Environment, Energy and Climate Change. Development of the projects sets the scene for a hydrogen economy in Greece and helps to meet various decarbonisation goals that have already been set out for Europe.

This development means that the projects in question are one step closer to being supported by European Union financial instruments and to participating in the emerging European hydrogen value chain. In particular, in a total of 20 dossiers submitted to the joint invitation of the Ministries of Development and Investment and Environment and Energy to submit proposals for projects that can compose the Greek participation in IPCEI "Hydrogen" were selected, after evaluation by a special Interministerial Committee of Experts, the following five projects: Blue Med, Green HIPO, White Dragon, H2CAT TANKS, H2CEM-titan.

Proposals approved by EU Member States participate in Challenge Sessions and related Workshops which are now coordinated at European level to encourage the development of collaborations between projects. According to the coordinators' categorization, the projects Green HIPo, White Dragon and H2CAT Tanks belong to the IPCEI sub-category "Hydrogen technologies" and Blue Med and H2CEM to the sub-category "decarbonization through hydrogen".

Following the approval and notification of the projects by the Member States, each scheme will be required to demonstrate to the European Commission that the projects are technically and financially mature, in accordance with the IPCEI criteria. Among other things, the innovative character, the proposed industrial utilization, the possibility of undertaking and successful implementation of the project by the interested party, the feasibility of the proposed projects, the spill-over effects and the completeness of business plans. The process will result in the precise determination of the financial gap, part of which will be covered by national and European aid.

The aim of the Greek participation in the first wave of IPCEI "Hydrogen" is to signal the beginning of a domestic hydrogen economy, through the implementation of the selected projects and its connection with the emerging pan-European hydrogen value chain. This will be achieved with the parallel creation of industrial scale units for the production, processing, storage and transport of hydrogen, but also the creation of domestic demand, initially catering to energy-intensive industrial consumers and continuing with the transport and navigation sectors.

The development of the hydrogen market is expected to make a decisive contribution to the achievement of the European goal of transition to climate neutrality by 2050. Hydrogen can play an important role in the further carbonization of the Greek energy mix and in the smooth energy transition environmentally friendly and fully compatible with the EU climate change strategy.

Finally, it is noted that according to the EU planning, Member States will be invited in the next period, to propose thematic units for the formation of the next "Hydrogen" waves, while the second IPCEI Hydrogen wave is launched after the completion of the ongoing planning.

## 6.1 Blue Med

A projector of Motor Oil which consists in the production of blue hydrogen with very low carbon footprint and green hydrogen, with a horizon of 2025. The project envisages the creation of a cluster of integrated production cycle of blue and green H2 for transport, distribution and use in industry and transport (buses and ships). The participation of DESFA and PPC companies as well as research institutes of the country is expected in the project.

## 6.2 Green HIPO

Project of Advanced Energy Technologies (Advent Technologies) for the construction of a production unit for innovative electrolysers and fuel cells. Combined heat and power (CHP) fuel cells are designed to be produced by Advent for Project White Dragon. The production will take place on the company’s production line, with installation in Western Macedonia.

## 6.3 White Dragon

Clusters of projects for the production of green hydrogen in Western Macedonia through electrolysis by solar energy and its distribution through the DESFA network and the TAP pipeline. DEPA Emporias SA participates in the project (as coordinator), Advent Technologies SA, COPELOUZOS GROUP (DAMCO ENERGY SA), Corinth Pipeworks SA, TAP AG, DESFA, the Hellenic Petroleum group of companies, MOTOR OIL and PPC.

A green hydrogen project set to support the phase out 2.1GW of lignite-fired capacity by 2029. The 250,000 tonnes of hydrogen/year project aims to use large-scale solar capacity to produce green hydrogen by electrolysis in the region of Western Macedonia for use in Greek heating and power, with an overall goal of replacing lignite plants .

## 6.4 H2CAT TANKS

Project of the company B&T Composites (TIRIAKIDIS VASILEIOS AETE) for the construction of innovative high-pressure tanks from composite material and carbon fibers for the storage of hydrogen, especially for the transport sector.

## 6.5 H2CEM - TITAN

Pioneer in the Greek Production of Cement using Green Hydrogen. The project concerns the production, storage and use of green hydrogen for combustion to produce energy in furnaces with the aim of decarbonizing the cement plants of TITAN.

# CHAPTER 7: SUMMARY

The reformation of fossil fuels involves extracting hydrogen from two inputs (a hydrocarbon fuel and water), while electrolysis only requires water. Because it is the hydrocarbon input that is causing the global warming problem that society is trying to solve, it would seem fundamentally wise to focus on hydrogen production processes based on water alone. The electrolysis of water using renewable electricity provides an immediately available pathway for producing high-purity hydrogen without causing global warming or atmospheric pollution. Accordingly, green hydrogen should be viewed as the priority for achieving a climate-neutral energy system.

It is essential that measures are put in place to ensure that hydrogen production has a zero-GHG footprint. For green and purple/pink hydrogen this is relatively straightforward, but blue hydrogen is characterized by significant residual emissions which need to be netted off with negative emissions. This can be achieved by several methods including afforestation, reforestation and by applying CCS to direct air capture and bioenergy production, but it adds cost.

By comparison, green hydrogen is both an economically attractive and environmentally benign option. In the short term, green hydrogen production can be achieved within the electricity grid at a scale appropriate to the demand level by locating electrolysers close to the points of hydrogen consumption. Importantly, rapid-response electrolysers can be operated to assist the integration of renewables into the grid, by providing a new market for electricity at times when generation is high, but demand is low. This approach can be engaged immediately and will enable hydrogen supply and demand to be grown progressively in the early market.

In the medium term it can be substantially augmented by off-grid electrolysis, which can produce hydrogen in bulk at low cost in regions of high renewable resource and feed it into a transcontinental hydrogen grid in a similar manner to that originally proposed in the 1970s for establishing a ‘hydrogen economy’. Accordingly, green hydrogen is increasingly being seen as the solution for achieving a climate-neutral energy system by 2050. This was recently expressed succinctly as ‘Renewable hydrogen and e-fuels are of critical importance to curb climate change. Without them, it will be impossible to achieve full decarbonization – and the clock is ticking.’

At present, governments are taking a rather centralized view of hydrogen; many are giving priority to green hydrogen, while some see green and blue hydrogen as one and the same. No established industry or supply chain has been lobbying for green hydrogen, but awareness of the green hydrogen approach appears to have increased recently, to the extent that it is now probably the preference of the general public.

Those who are uncertain or believe in 'technology neutrality' as a supreme principle, default to grouping blue and green hydrogen together, and overlook their distinct attributes. This is an unsatisfactory stance, and more detailed assessments of hydrogen derived from fossil fuels versus hydrogen derived from renewable energy are required. In particular, it is important for governments to place a focus on realizing the opportunities provided by the green hydrogen pathway, by working with the relevant industry stakeholders to establish effective policies and business models for initiating and growing markets in the industrial process, transport and heat sectors.

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3. Directive 2014/68/EU - On the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment (recast).
4. Directive 2001/42/EC - On the assessment of the effects of certain plans and programmes on the environment (SEA).
5. Directive 2014/52/EU - Amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (EIA).
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