POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Regulatory framework in hydrogen production and the opportunities for application to a Mobility case study

TESI DI LAUREA MAGISTRALE IN
MOBILITY ENGINEERING

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Academic Year: 2021-22

Preface

Thesis developed in collaboration with a2a S.p.A. Hydrogen Unit.

Trenord S.r.l. and FNM Group supported the document for the H2iseO project part.

Abstract

In the international scientific and institutional world, the need for action that can no longer be postponed for the mitigation of extreme climate phenomena and their associated consequences is shared more than ever. Institutional choices, strategies, and visions have been developed since the end of the last century, and are being updated and improved from time to time. In this context, technologies that may matter in the decarbonization process, especially new or uncommonly deployed ones, need to find the button in legal regulation to be able to demonstrate their potential. In other words: they must be able to be applied and enforceable. Such is the case with hydrogen. In this thesis, after reporting the major technologies available to date for hydrogen production, and through the analysis of the legal/regulatory framework, we come to identify which of them are the most environmentally sustainable through a definition of "green hydrogen." Subsequent to this analysis, a case study is identified: the production of green hydrogen from electrolysis, through the exploitation of biogenic waste combustion from a2a Brescia Waste-to-energy as renewable energy, for the development of a hydrogen value chain in the established camuna Hydrogen Valley. Through interviews with the Hydrogen Unit Manager and a2a Regulatory Affairs contact persons, the emissions data resulting from the downstream methodology (LCA) used are compared and contrasted with what is required by the regulations previously analysed. The result shows this production mode is compliant with the regulations, and therefore in this case it is correct to speak of green hydrogen. Furthermore, for the purpose of understanding the viability of the project, the LCOH of the electrolyser that is used with baseload energy is compared with that which uses other intermittent renewable sources such as sun and wind. In this case, the virtuosity of this type of production while maintaining a lower cost of hydrogen is highlighted.

Key-words: Green hydrogen, regulation, Waste-to-Energy, electrolysis, hydrogen valley.

Abstract in italiano

Nel mondo scientifico ed istituzionale internazionale è più che mai condivisa la necessità di interventi non più rinviabili per la mitigazione dei fenomeni climatici estremi e le conseguenze ad essi associate. Le scelte, le strategie e le vision istituzionali sono state elaborate sin dal finire del secolo scorso, e vengono di volta in volta aggiornate e migliorate. In questo contesto, le tecnologie che possono avere importanza nel processo di decarbonizzazione, soprattutto le nuove o quelle poco diffuse, devono trovare nella normativa legale il punto d'aggancio per poter dimostrare le loro potenzialità. In poche parole: devono poter essere applicate ed applicabili. E' questo il caso dell'idrogeno. In questa tesi, dopo aver riportato le maggiori tecnologie ad oggi disponibili per la produzione di idrogeno, ed attraverso la disanima del quadro normativo/regolatorio si giunge ad identificare quali di esse sono le più sostenibili ambientalmente attraverso una definizione di "idrogeno verde". Successivamente a questa analisi, viene identificato un caso studio: la produzione di idrogeno verde da elettrolisi, attraverso lo sfruttamento della combustione di rifiuto biogenico da Termoutilizzatore come energia rinnovabile, per lo sviluppo di una catena del valore dell'idrogeno nella costituenda Hydrogen Valley camuna. Attraverso le interviste al Responsabile dell'unità Idrogeno ed ai referenti di Affari regolatori di A2A, vengono confrontati i dati sulle emissioni che risultano a valle della metodologia (LCA) utilizzata e confrontati con quanto previsto dalla normativa analizzata in precedenza. Il risultato evidenzia la congruenza di questa modalità di produzione con la normativa, e quindi in questo caso è corretto parlare di idrogeno verde. Inoltre, allo scopo di comprendere l'attuabilità del progetto, si compara il LCOH dell'elettrolizzatore che viene utilizzato con baseload di energia con quello che utilizza altre fonti rinnovabili intermittenti quali sole e vento. In questo caso si evidenzia la virtuosità di questo tipo di produzione, mantenendo un costo dell'idrogeno più basso.

Parole chiave: idrogeno verde, normativa, termoutilizzatore, elettrolisi, hydrogen valley.

A Alice e Linda, che costruiscono il futuro.

Contents

Introduction

1.1. Environmental Actions Program - History and EU Strategies

Rio Declaration [1] on Environment and Development in 1992 was produced at the United Nations "Conference on Environment and Development" (known as the Earth Summit). It is the cornerstone of the sustainability approach. The Rio Declaration consisted of 27 principles intended to guide countries in sustainable development.
The Convention on Climate Change produced in Rio would lead to the Kyoto Protocol[2] - 1997. It worked by committing industrialized countries and economies in transition to limit and reduce Greenhouse gases (GHG) emissions in accordance with agreed individual targets. The Protocol itself only asks those countries (under the principle of "common but differentiated responsibility and respective capabilities") to adopt policies and measures on mitigation.
The Intergovernmental Panel on Climate Change (IPCC), the principal international organization that researches climate change and works under the framework of the United Nations, whose task is to assess: the risk of human-induced climate change, its potential impacts, and possible options for prevention; and *Copernicus* (the European Union's Earth observation program dedicated to monitoring the planet and its environment) offer information on long-term evolution of a number of key factors used to evaluate the global and regional patterns of a changing climate. Those are the climate indicators in Figure 1.

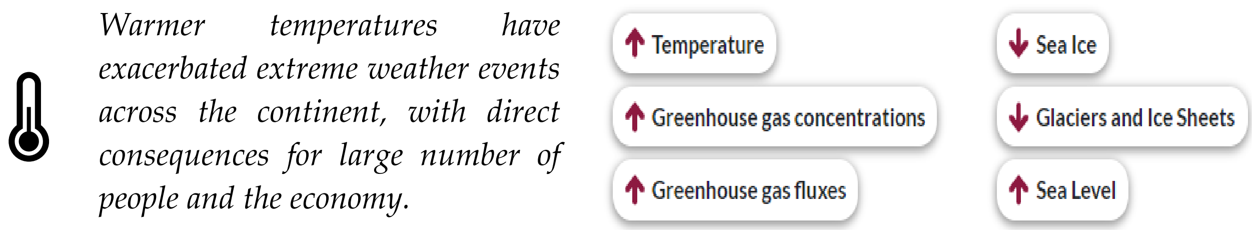


Figure 1- Climate indicators factor

Global warming is unmistakably a result of human activity, according to the most recent Report of IPCC [3].

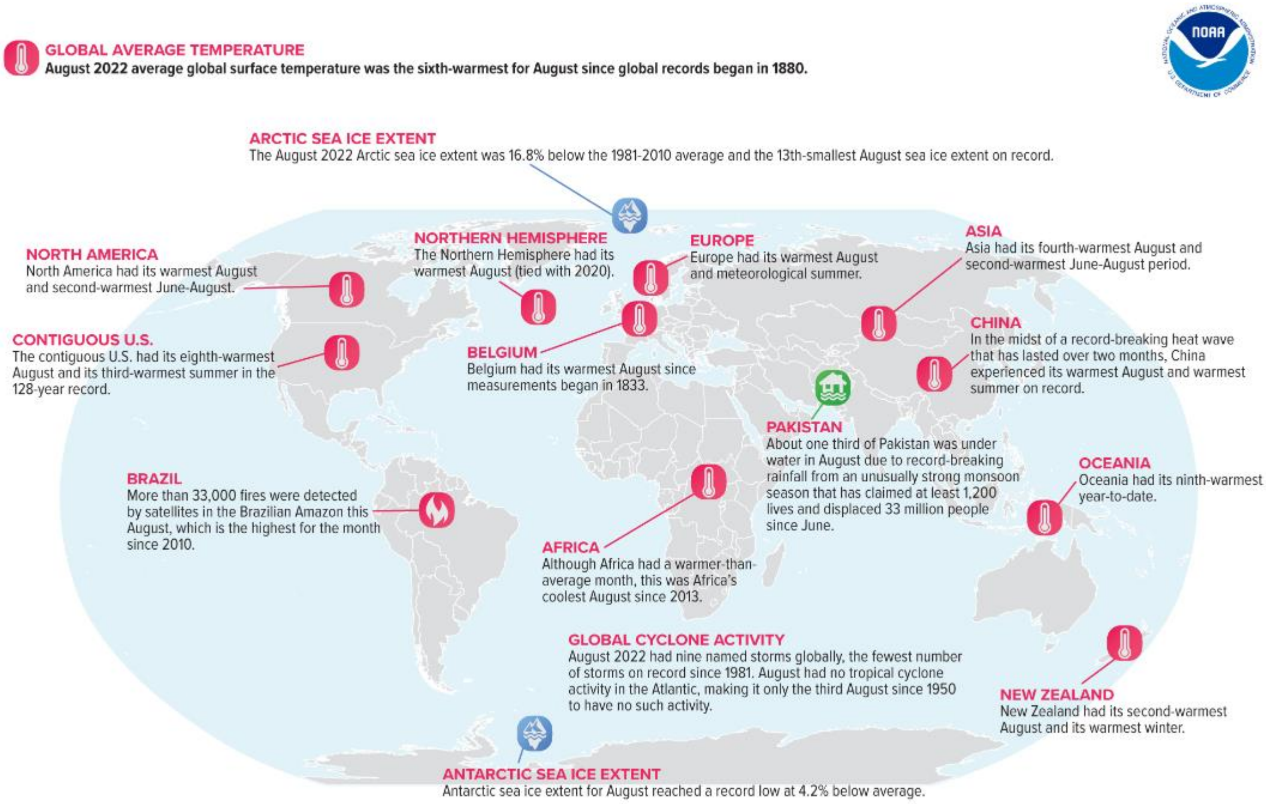


Figure 2 - Source: NOAA National Centers for Environmental Information, State of the Climate.

The number of unpredictable occurrences, like those showed in Figure 2, that are dangerous to people and causes economic losses has increased as a result of rising temperatures.

Figure 3 - Source: https://www.consilium.europa.eu/en/infographics/climate-costs/

1.2. The transition to a climate neutrality

The goal that has been set to avoid further temperature increases on the planet and mitigate the negative effects associated is carbon neutrality or climate neutrality, then zero-emission as the net balance between GHG produced and contained.
The European Union has been moving toward decarbonization for several years in order to deal with emerging climate emergencies.

1.2.1. The European Environmental Action Programs – GHG Reduction

Since 1973, the European Commission has been issuing multi-year Environmental Action Programs that set out future legislative proposals and objectives for the Union's environmental policy.
About the emissions the European institution delivers the following in the respective years:

- 2007: The European Commission presented targets of greenhouse gases reduction (30% compared to 1990 levels) by 2020 in international negotiations and to reduce its domestic emissions by at least 20% by 2020. The European Council approved the objectives of reducing emissions of greenhouse gases presented by the commission.
- 2008: The European Commission presented the definitive package and promoted renewable energies which was adopted by the European Parliament. The "Climate and Energy Package," first issued by the European Union in 2008, established circularity goals to be met by 2020. This was followed by a modification that set new goals for 2030.

1.2.2. The COPs and the overcoming of the Kyoto protocol

The 2009 World Climate Conference in Copenhagen led to an international agreement to succeed the Kyoto Protocol on climate change, which expires at the end of 2012.
The Conference of the Parties (COP 21) was held in Paris in 2015. It was the organization's 21st annual session.
For the first time in more than 20 years of discussions, the 2015 conference aimed to bring all countries of the globe together to negotiate a legally enforceable agreement on climate change within the United Nations (UN).
The Paris Agreement [4] creates a framework for preventing severe climate change on a global scale by keeping temperature to below 2°C and stepping up efforts to keep it to 1.5°C. Moreover, it seeks to increase nations' ability to deal with the effects of climate change; Finally, it establishes the objective of making financial flows consistent with a pathway to low greenhouse gas emission development, among other means, to improve the response to climate change.
It is the first global agreement on climate change that is enforceable by law.

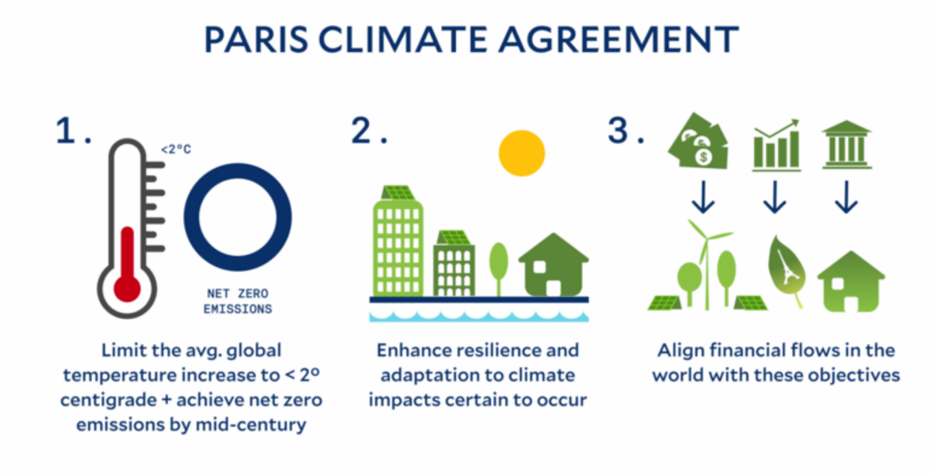


Figure 4 - Paris Climate Agreement targets. Source: https://www.cdmdna.gov.sa/page/14

In light of this, the EU and its member states are among the Paris Agreement's roughly 190 Parties. The European Union formally accepted the agreement, allowing it to go into effect on November 4, 2016.

1.2.3. Climate-Energy Package 2020 and Circular Economy

The Climate-Energy Package 2020 [5] was a milestone in the European Union's climate change policy. The so-called 20-20-20 targets include reducing GHG levels by 20 percent, increasing the share of renewable energy by 20 percent, and reducing energy consumption by 20 percent until 2020. The targets of the 2020 climate & energy package [6] were set by EU leaders in 2007 and enacted in legislation in 2009. The EU is acting in several areas to meet the targets.

The "Climate and Energy Package," first established circularity goals to be met by 2020.

The circular economy was subsequently recognized by the EU as a priority strategy to increase European competitiveness from a sustainable perspective through 54 initiatives in December 2015. Several plans with medium- to long-term objectives and the appropriate resources were released throughout the following years.

This package was followed by a modification in which more ambitious goals were then set for 2030: a 40% reduction in emissions, a 32% contribution from renewable energy, and a 32.5% increase in energy efficiency.

At the end of 2019, as required by the European Union Governance Regulation, member states sent their Energy and Climate Plans, for the period 2021-2030, to the Commission, listing their initiatives and their contribution to the above-mentioned climate goals.

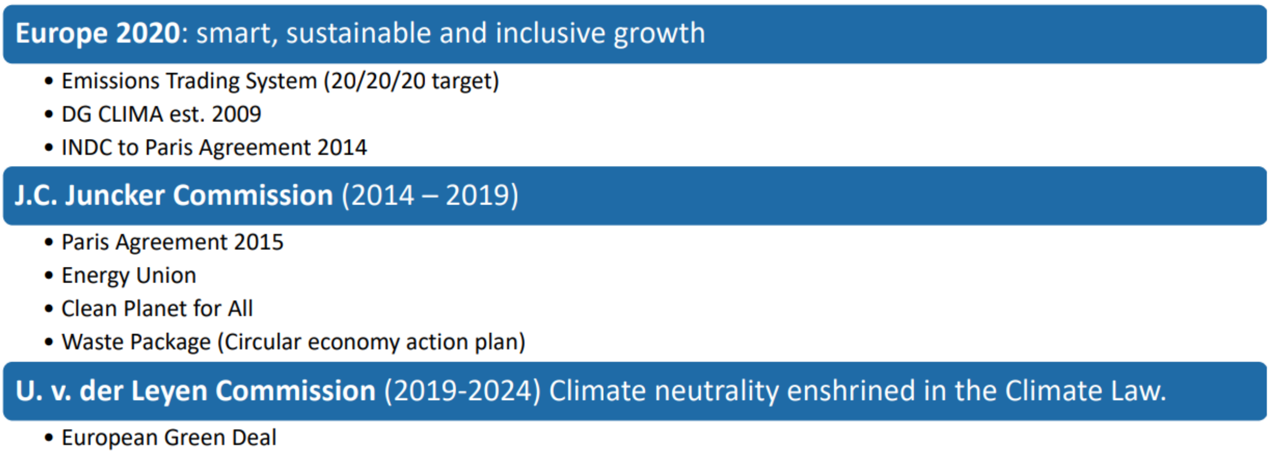


Figure 5 - Source: European Roundtable On Climate Change And Sustainable Transition-20210928-ERCST-presentation-EDG-presented.pdf

1.3. The European Green Deal

The main growth strategy of the EU for converting the European economy to a sustainable economic model is the Green Deal. The EU wants to become the first climate-neutral continent by 2050, with a cleaner environment, more affordable energy, smarter transportation, new jobs, and an overall higher standard of living, according to the Green Deal, which was disclosed in December 2019. Several financial mechanisms, totalling more than 1 trillion euros are intended to support the EU Green Deal.

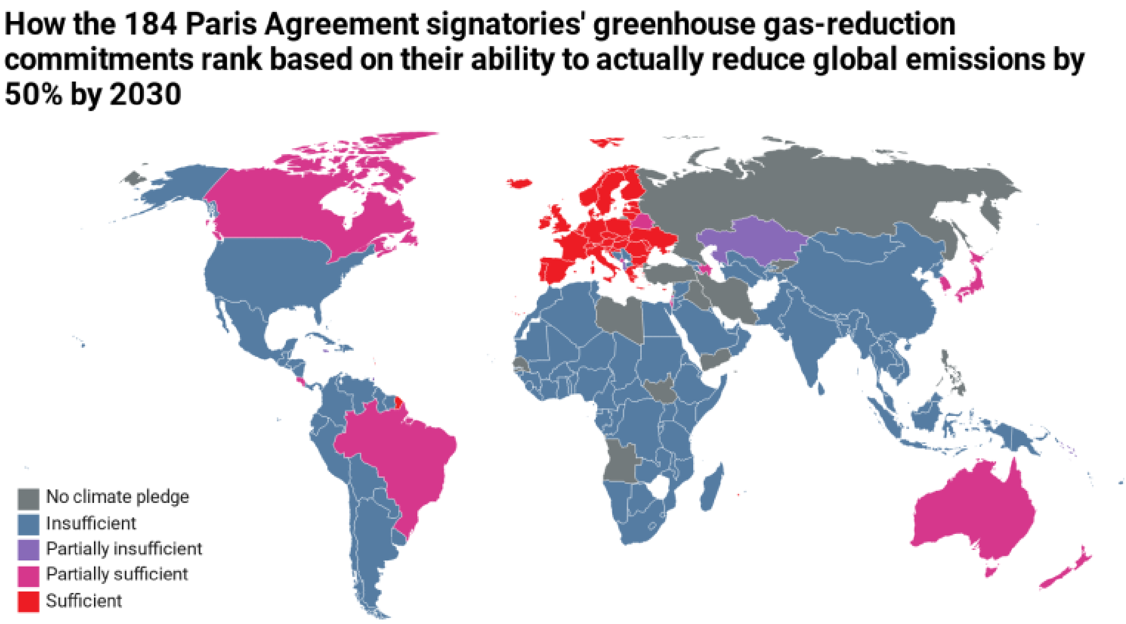
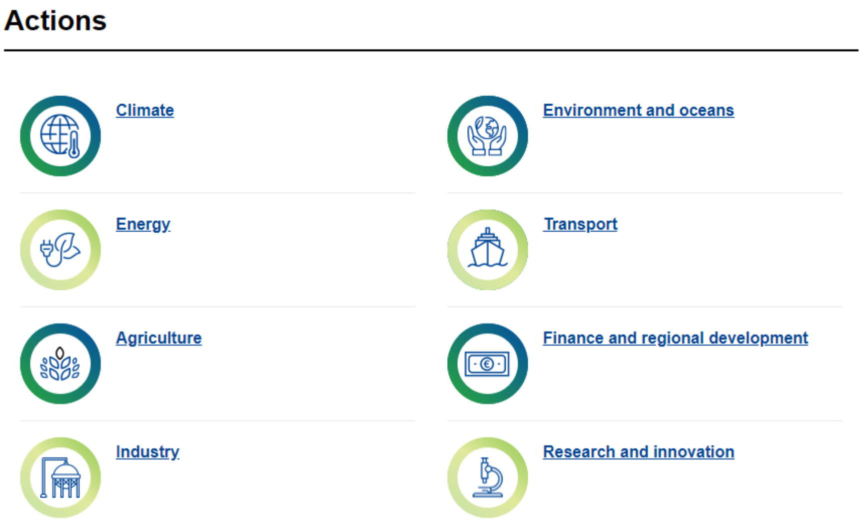


Figure 6- Europe comes out ahead of other countries in reducing emissions Source: Foundacion Ecologica Universal (FEU-US) - Created with Datawrapper

The main elements of the EU Green Deal are reported in Table 1:

Table 1 - Source: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en



Climate action

A central goal of the EU Green Deal is to set the trajectory for making the EU climate neutral by 2050. To achieve this goal, the EU Commission has proposed a 2030 target to reduce greenhouse gas emissions by 55 percent compared to 1990. This 2030 target must reflect the European Climate Act, which has climate neutrality as its goal.

Clean energy

Currently, more than 75% of the EU's greenhouse gas emissions are attributable to the production and consumption of energy in various economic sectors. By creating an energy sector that is predominantly based on renewable resources and an integrated, networked, and digitalized EU energy market, the "Clean Energy" area seeks to lower this number.

The EU Hydrogen Strategy [7] investigates how clean hydrogen could aid in the decarbonization process. The selected approach encourages the development of electrolysers technology.

The Energy Systems Integration Strategy, which intends to enhance coordination of the planning and operation of the energy system "as a whole" across various energy carriers, infrastructure, and end uses, will be made easier by the Clean Energy for All Europeans package.

It has also been suggested to update the Trans-European Energy Networks Regulation (TEN-E Regulation) [8]. The updated framework considers the quick uptake of renewable energy, modernisation of the EU's transnational energy infrastructure and the requirement of sustainability requirements for all projects.

These EU projects will complement one another and work together to build the groundwork for a decarbonized European energy system.

Sustainable Industry

Currently, 20% of the EU's GHG come from industry. Therefore, measures to support the decarbonization efforts are included in the EU Green Deal, spanning from the supply of raw materials to the sustainability of products. The Circular Economy Action Plan [9], which has been accepted, includes attempts to lengthen the life of a product in order to lessen the strain on natural resources. It also has a policy on sustainable products that governs the enhancement of product repairability, reusability, and integration of recycled materials. The accepted EU Industrial Strategy aims to create markets for environmentally friendly and circular products and to promote the EU's digital transformation. The EU Green Deal states that these steps are required to guarantee the availability of the essential raw materials.

Buildings and renovation

In the EU, buildings account for 36% of energy-related GHG emissions and 40% of total energy consumption. "Cleaner" buildings and the construction industry are necessary to achieve the goals of the EU Green Deal. Buildings can be renovated as part of the Renovation Wave [10] to become more energy efficient. It prioritizes the decarbonization of heating and cooling, addressing the stock of buildings that performs poorly, and renovating public structures like schools and hospitals. Priority will be placed on improving building energy efficiency, and the EU Commission will look into the prospect of incorporating building emissions in the EU Emissions Trading System (EU ETS).

Sustainable Mobility

Initiatives to reduce transportation emissions, which make up 25% of the EU's GHG emissions, are included in the sustainable mobility policy area. The agreed Strategy for Sustainable and Smart Mobility [11] establishes the framework for action to reform the EU transportation industry with the goal of a 90% reduction in emissions by 2050, achieved through a smart, competitive, safe, accessible, and cheap transportation system. The promotion of more environmentally friendly modes of transportation might lead to increased capacity, lessened congestion, and less pollution. The approach includes the following aims for 2030: high-speed rail traffic will double throughout Europe, 100 European cities will be climate neutral, scheduled collective travel for trips under 500 km should be carbon neutral, automated mobility will be widely adopted, and zero-emission marine vessels will be market-ready, with additional goals for 2035 and 2040.

A variety of amended law proposal ideas are being taken into consideration in order to achieve these goals. The Directive on the Deployment of Alternative Fuel Infrastructure, which establishes the specifications for growing the EU's network of refuelling and charging facilities for alternative vehicle fuels including hydrogen and electric batteries, is one part of the assessment.

In view of the EU's goal of being carbon neutral by 2050, the regulation establishing CO_2 emission performance criteria for new light commercial vehicles and passenger automobiles may also be changed. For road cars, the modification would mean tougher pollution limits. The Trans-European Transport Network Regulation (TEN-T Regulation) [12]and the Intelligent Transport Systems Directive [13] are both slated for change by the EU Commission. This intends to boost digitalization and automation, enhance the use of zero-emission cars, and provide sustainable alternatives.

Batteries will be crucial for the adoption of electric vehicles as well as the restructuring of the energy grid. Because of this, EU legislation also places a strong emphasis on environmentally friendly battery supply chains that encompass the complete battery life cycle, including recycling and reusing. The European Commission aims to boost the sustainability of supply chains and enhance recycling of industrial, automotive, electric vehicle, and portable batteries sold in the EU with its proposal for a Regulation on batteries and waste batteries.

The modification of EU ETS regulations for the aviation industry, as well as a review of suggestions to reduce free allowances assigned to the industry, are included in the EU Commission's work plan.

The upgrade would put the worldwide aviation carbon offsetting and reduction plan into effect. In addition, the EU Commission suggests expanding the EU ETS to the marine industry and, pending an impact analysis, to road transport.

<u>Eliminating pollution</u>

Premature deaths and a variety of physical and mental disorders are mostly brought on by pollution. The European Commission has suggested a Zero Pollution Action Plan as a result. This proposal intends to further uncouple economic growth from rising pollution levels by including pollution reduction strategies into all policy activities. Three key initiatives are included in the action plan to reduce pollution. First, a chemical sustainability plan to save the environment from dangerous substances. Second, a "zero pollution" action plan for soil, water, and air [14] that will improve pollution prevention, correction, oversight, and reporting. Lastly, an evaluation of pollution control measures for sizable industrial sites to make sure they align with the EU's Green Deal objectives.

<u>Farm to Fork</u>

Food systems employ a lot of natural resources and contribute between 21 and 37 percent of the world's GHG emissions. Reduced waste and altered food production, processing, retailing, packaging, and transportation processes are the main goals of the Farm to Fork plan.

Separately, a plan to lower methane emissions has been put up by the European Commission. After carbon dioxide, methane is the second-largest cause of climate change and air pollution. Methane emissions must be reduced across all sectors; in the EU, agriculture accounts for 53% of anthropogenic methane emissions, followed by waste (26%), and energy (19%). In addition to targeted actions in the energy, agricultural, and waste sectors, the methane plan also focuses on prospects for biogas generation and accurate reporting.

Preserving Biodiversity

According to the EU Biodiversity Strategy 2030, overpopulation, climate change, pollution, and the introduction of invasive alien species are the main causes of biodiversity loss. The loss of biodiversity and climate change are connected, and natural solutions will be crucial for both reducing climate change's effects and adapting to it. Construction, agriculture, and the food and beverage industries are among those that largely rely on biodiversity, according to the European Commission. Together with the Farm to Fork plan, the EU's biodiversity policy will put an emphasis on restoring wetlands, soils, and forests as well as developing green spaces in urban areas. The EU will put in place a new biodiversity governance framework to overcome legal gaps that impede raising biodiversity standards across the whole EU.

Research and development

The EU Green Deal's individual components are supported by research and development. A large number of EU Green Deal activities call for the adoption of new technology as well as the transformation of supply networks and finance structures. The funding for these R&D projects will come from Horizon Europe [15], which has committed nearly 35% of its € 95.5 billion budget to meeting EU climate goals.

In order to concentrate on important sectors including batteries, clean hydrogen, low-carbon steel, the built environment, and biodiversity, the EU will create green partnerships with a variety of companies and its member states under Horizon Europe.

Preventing unfair competition from carbon leakage

The EU Green Deal will necessitate a considerable shift in the EU economic model toward a low carbon one. There is a chance of carbon leakage as a result of this. This is the danger, according to the EU Commission, of either having production moved from the EU to other nations with lower emission reduction goals or having EU products substituted by imports with higher carbon footprints. The free distribution of permits under the EU ETS or compensation for energy-intensive companies affected by higher power bills as a result of carbon pricing under the EU ETS are being used to reduce carbon leakage. Therefore, in order to ensure that the price of imports more correctly reflects their carbon content, the EU Commission is proposing a Carbon Border Adjustment Mechanism [16] . This action is proposed to be designed to comply with World Trade Organization rules and other international obligations of the EU.

1.3.1. The “Fit for 55” package

The so-called "Fit for 55" package of 13 legislative proposal, presented by the European Commission in 2019, aims to accelerate the decarbonization process (which was subsequently approved in 2021). It contains 5 new ideas as well as 8 changes to existing legislation acts. The overarching objective of the "Fit for 55" program is to accomplish the European targets for the energy transition to 2030, which were first agreed upon on October 23, 2014, and enhanced in 2018.

The Fit for 55 package gives the preparation road to fulfil the aims of the European Green Deal, whereas the latter is a general action plan to combat climate change. Fit for 55 concentrates on certain issues that require special consideration and a significant green transition to attain climate neutrality. This plan specifically intends to cut GHG emissions by 55% by 2030 (compared to 1990 levels).

The package's main goals consist of the following:

- Guaranteeing environmental integrity and addressing solidarity;
- The EU ETS will be tightened and strengthened, helping to ensure effort sharing with relevant targets;
- Additional policies will help ensure the implementation of carbon prices;
- All revenues from carbon pricing aim to positively influence final consumers.

The package has been described in evocative ways, such as the "mammoth package" in reference as the most substantive and all-encompassing package adopted by the Commission on climate and energy policies to date, transforming the EU economy and society in order to realize climate ambitions.
The "Fit for 55" package will significantly modify how we utilize, and occasionally abuse, energy.
The following are proposed improvements to existing legislation:

- Proposal for a DIRECTIVE amending Directive (EU) 2018/2001 (RED II) as regards the promotion of energy from renewable sources [17]
- Proposal for a DIRECTIVE on energy efficiency (recast) – amending Directive (EU) 2012/27 [18]
- Proposal for REGULATION on the deployment of alternative fuels infrastructure, repealing Directive 2014/94/EU [19]
- Proposal for a DIRECTIVE restructuring the union framework for the taxation of energy products and electricity (recast) [20];
- Proposal for a DIRECTIVE amending Directive (EU) 2003/87/Ce on Emission Trading, the Decision 2015/1814 and the regulation 2015/757/UE [21];
- Proposal for a DIRECTIVE amending Directive (EU) 2003/87/Ce on emission trading as regard the contribution of air transport to the reduction of greenhouse gas emissions;

- Proposal for a decision amending Directive (EU) 2003/87 on emission trading as regards the notification of compensation in relation to a global market-based measure for aircraft operators;
- Proposal for REGULATION amending regulation 2018/842 on annual greenhouse gas emission reductions 2021-2030 in non-ETS sectors;
- Proposal for REGULATION amending regulations 2018/841 and 2018/1999 for climate neutrality to 2035 in the area of land use, forestry, and agriculture (Lulucf)[22];
- Proposal for REGULATION establishing a carbon border adjustment mechanism [16].

This revision is expected to be effective when member states begin updating their national energy and climate plans in 2023, so that these plans reflect the new climate ambitions.

"Fit for 55," also outlines strategies to support businesses and territories on the path to decarbonization.

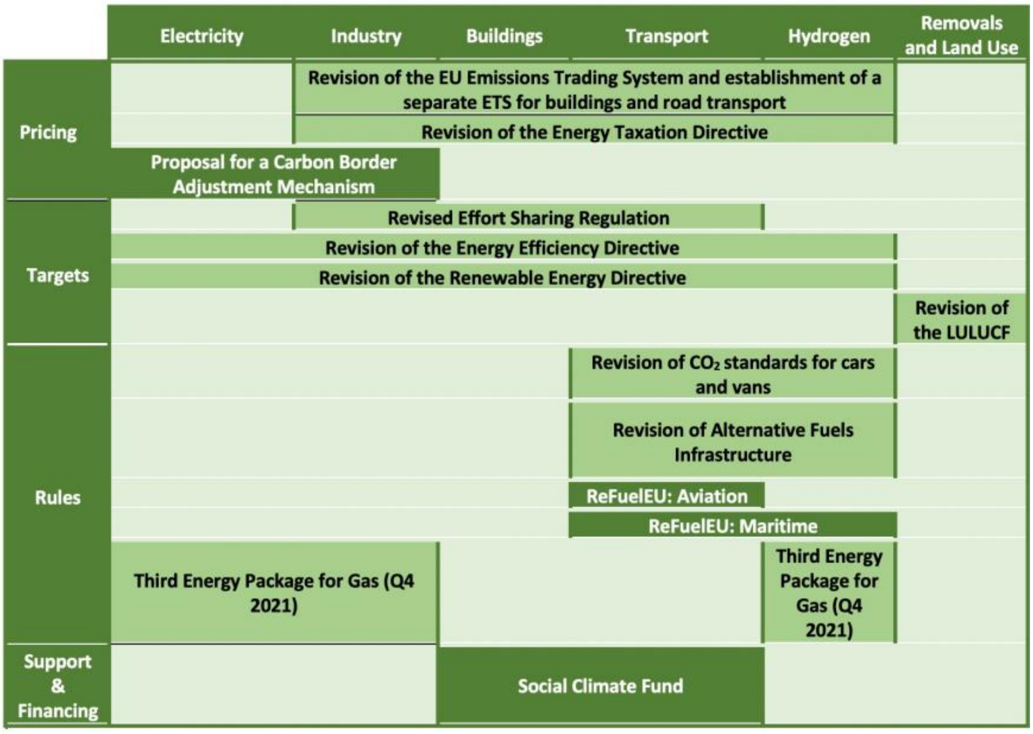


Figure 7- FIT FOR 55 Mapping of interactions

Source: "State of the European Green Deal"- ERCTS presentation, September 2021

1.4. Financial framework supporting the transition

1.4.1. Multiannual Financial Framework and NextGenerationEU

To facilitate the transition, and the exit from the situation created by the COVID-19 pandemic, the European Commission has adopted a long-term budget for 2021 to 2027: the Multiannual Financial Framework (MFF)[23]. Together with the NextGenerationEU Fund (NGEU) [24] unveiled in May 2020, amounts to over EUR 1.8 trillion, of which 30 percent of MFF and 37 percent of NGEU will be dedicated to supporting climate action (European Green Deal).

In addition, cohesion policies focus on activities related to the green and digital transition, for which 721.9 billion of euros; EU funds and programmes enable like: Energy and Environmental State Aid Guidelines, Innovation Fund, Invest EU 2021, Circular Economy Finance Support Platform, LIFE Programme and Social Climate Fund; the research sector is also increasingly pushing for environmentally sustainable solutions: with the Horizon program [15], 28.1 billion Euro to support energy transition; and private investment.

With the help of this investments, the EU will be able to undertake the necessary policy changes for both economic expansion and climate neutrality.

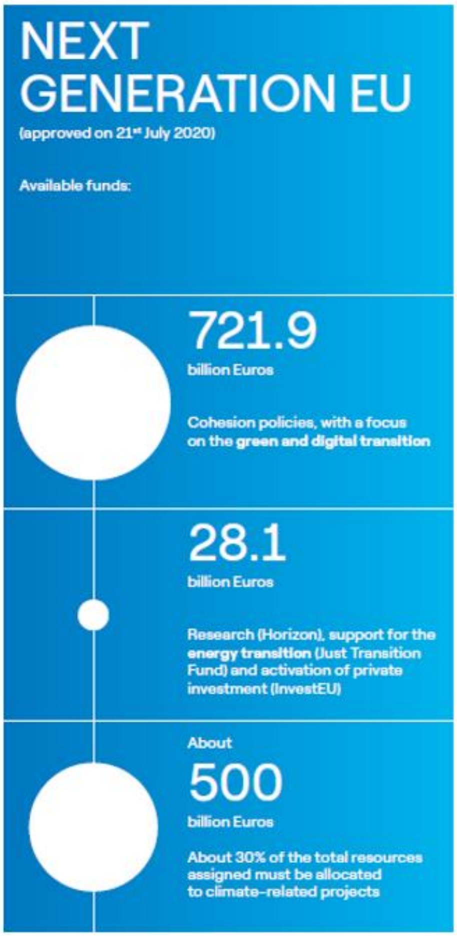


Figure 8 - NGEU funds.[85]

1.4.2. Sustainable Finance and Taxonomy

To achieve the policy goals set out in the European Green Deal and the EU's international climate and sustainability obligations, sustainable finance[25] must play a key role in mobilizing the necessary capital. It ensures that investments support a strong economy and long-term recovery from the effects of the COVID-19 pandemic.

The Taxonomy Regulation [26] (EU taxonomy for sustainable activities) is a standardized classification system created by the EU that gives the financial industry, which must specify how environmentally sustainable an investment actually is;

governments, which must create incentives for green businesses; and corporations, which must reveal their environmental impact, with the proper definitions for which economic activities can be considered (and define themselves) as environmentally sustainable.

Through this tool, the EU is primarily aiming to reduce market fragmentation, provide investor security, and also get ahead of greenwashing. Helping businesses become more environmentally friendly and focus investments on sustainable projects and activities is another essential objective that will boost the probability that global climate and energy targets will be met.

Interesting implication is that this regulation and its implementation will also increasingly affect the design of those infrastructures that will play a central role in development (and thus be eligible for European funding). Indeed, compliance with the EU Taxonomy and its implementing documents is required.

The Regulation entered into force on July 12, 2020. It sets the basis for the EU Taxonomy by establishing three general conditions or "technical selection criteria," that an economic activity must meet in order to qualify as environmentally sustainable:

1. contribute substantially to one of six environmental objectives: climate change mitigation, climate change adaptation, sustainable and protection of water and marine resources, transition to a circular economy pollution prevention and control, and protection and restoration of biodiversity and ecosystems.
2. do not cause significant harm (DNSH) to none previous of the environmental goals
3. Be carried out in compliance with minimum social guarantees (e.g., those stipulated in Organisation for Economic Co-operation and Development -OECD- guidelines and UN documents).

With reference to the concepts of "substantial contribution" and "not causing significant harm," the Taxonomy sets the technical screening criteria for the achievement of each environmental objective by declining them on the different economic macro-sectors (defined as "transitional" because they will have to face the challenge of energy changes) and for individual activities related to them. Here is the list of economic macro-sectors under the taxonomy:

- Forests
- Environmental protection and restoration activities
- Manufacturing
- Energy
- Water supply, sewerage, waste management, remediation
- Transportation
- Construction and real estate
- IT and communications
- Professional, scientific, and technical activities

- Financial and insurance activities
- Education
- Health care and social services
- Arts, entertainment, and recreation

The EU Commission must establish technical selection requirements by delegated acts in accordance with the Taxonomy Regulation [27].
EU Taxonomy on Climate Goals' first delegated act establishes guidelines for economic activity in fields vital to achieving climate neutrality and combating climate change. These include the manufacturing, transportation, forestry, construction, and energy sectors.
The second delegated act concerns the inclusion of specific energy activities of the gas and nuclear sectors in the list of sustainable economic activities. In this sense, classifying some energy activities related to natural gas and nuclear energy as transitional activities that contribute to climate change mitigation will encourage private investment in the green transition activities of the gas and nuclear sectors.
In general, Regulations will impose disclosure rules on selected companies and investors, requiring them to disclose the percentage of transactions that adhere to the taxonomy. Comparison between companies and investment portfolios will be possible through disclosure of the percentage of assets that match the taxonomy. In addition, it can help market participants make informed investment choices. If they wish, companies can reliably plan their climate and environmental transition and secure related financing using the EU taxonomy. If they wish, financial institutions can create reliable green financial products using the EU Taxonomy. However, the EU Taxonomy is not a list of economic activities in which investors are required to invest. It also does not impose binding environmental performance standards on companies or financial products.

1.5. RePower EU

The conflict between Russia and Ukraine, which broke out in February 2022, has increased the urgency of climate action in Europe and has significant effects on the energy framework and the export of energy commodities, primarily natural gas, from Russia. It has also brought attention to the need for European nations to increase their energy independence from other countries. It is sufficient to recall that in 2020, almost three quarters of the extra-EU crude oil imports came from Russia (29 %), the United States (9 %), Norway (8 %), Saudi Arabia and the United Kingdom (both 7 %) as well as Kazakhstan and Nigeria (both 6 %). A similar analysis shows that over three quarters of the EU's imports of natural gas came from Russia (43 %), Norway (21 %), Algeria (8 %) and Qatar (5 %), while more than half of solid fossil fuel (mostly coal) imports originated from Russia (54 %), followed by the United States (16 %) and Australia (14 %). [28]

Energy dependence is particularly serious in nations like Germany and Italy, which together account for 25% of the EU-27's total imports of Russian oil and 52% of its total imports of Russian gas.
To ensure energy security and reduce dependence on Russian gas, the European Union responded to this emergency situation by launching a new EU program, the REPowerEU [29]. The Plan, calls for reducing final energy usage from the "Fit for 55" package's 787 Mtoe to 750 Mtoe beginning in July 2021 and increasing the proportion of renewable energy in final energy from 40 to 45 percent in 2030, and consists of 3 pillars that revise upward the targets set by previous national and European energy packages:

- saving energy
- producing clean energy
- diversifying our energy supplies

A first response of the European Union to the current energy crisis is the "Save Gas for a Safe Winter" (SGSW) plan [30] . The plan, which was disclosed in July 2022, intends to increase European energy security, lower risks, and costs for member states in the case of gas supply disruptions, and offer pre-established processes for handling the challenging circumstances that would arise in the next winter. By March 31, 2023, the plan's ultimate objective is to cut the gas consumption for European nations of 15%. This was followed by the Regulation adopted by the European Council on a voluntary reduction of natural gas demand by the member states of that quantity and includes the possibility of the Council activating a "state of alert of the Union" for security of supply; in that case the gas demand reduction would become mandatory. [31]
One of the goals of the second pillar is to increase the "Fit for 55" target of final energy consumption from 40 to 45 % renewable energy sources (RES). Additionally, the EU has a solar policy that aims to double Photovoltaics (PV) capacity by 2025. "Solar Rooftop," which mandates the installation of solar panels on new buildings, and suggestions to resolve crucial concerns connected to sluggish and challenging permitting for the development of significant RES projects.
Within the third pillar, to diversify energy sources, has been places a lot of emphasis on the **development of hydrogen**, with a goal of producing 10 million tons of renewable hydrogen domestically and importing 10 million tons by 2030. In the Commission Staff Working Document on REPowerEU, “Hydrogen Accelerator” is the largest part of the document. The following conclusions about the development of hydrogen imply that is needed for the Commission:

- develop periodic progress reports, starting in 2025, on the production, transport, and adoption of renewable hydrogen in industry and transport;
- develop harmonized hydrogen quality standards to support their adoption in priority sectors;

- to provide guidance on applicable standards and procedures for the construction and operation of future infrastructure to help accelerate and (further) streamline permitting procedures for hydrogen projects;
- To define hydrogen market operation and technical issues as a first step toward establishing a European network of hydrogen network operators;
- To develop, based on the TEN-E regulation, the priorities of the European hydrogen infrastructure;
- Establish the European Global Hydrogen Fund in collaboration with member states to support the creation of a regulatory framework for renewable hydrogen partnerships, facilitate EU-wide coordination on international hydrogen projects, and incentivize European and global renewable hydrogen production;
- double the number of hydrogen valleys by 2025 by enhancing Horizon Europe's investment in the Hydrogen Joint Undertaking to deliver solutions with citizen engagement, in regional innovation ecosystems, across the entire hydrogen value chain.

Additionally, a new action plan for biomethane has been created, with a production goal of 35 billion m^3 annually by 2030, almost twice that set by the "Fit for 55" of 18 billion m^3.
In order to enable the joint supply of methane, LNG (Liquid Natural Gas), and hydrogen, an EU energy platform has been designed.
Without improvements on the demand side and an increase in consumption efficiency, the creation of new energy supply networks and supply techniques cannot ensure adequate levels of energy autonomy. For this reason, the REPowerEU wants to increase the "Fit for 55" energy efficiency binding objective for the entire European Union in 2030. This action is consequently complemented with budgetary initiatives to promote energy conservation, with the hope that short-term behavioural modifications may lower the demand for gas and oil by 5%.

1.6. The Italian National Policies framework

The Italian government has integrated and adapted the European directives on green transition through new and targeted national programs.
The National Energy Strategy (SEN) was presented on November 10, 2017, for managing the transition of the energy system, which aimed to achieve by 2030: a 28% share of renewable energy sources (RES) in total consumption, an amount of CO_2eq emissions of 332 Mtons, and a final energy use of 108 Mtoe.
These targets were updated in 2019 through the National Integrated Energy and Climate Plan (PNIEC), sent to the European Commission in 2020. The PNIEC increases the share of RES in total consumption to 30 percent, 328 Mtoe of CO_2eq emissions and 103.8 Mtoe of energy end-use by 2030.

The packages described in the sections before represent Italy's medium-term goals and directions. The Italian Long-Term Strategy (LTS), developed by the government in 2020, operates as a supplement to this view. The steps required to reach the 2050 climate neutrality envisioned by the European Green Deal are listed in this paper. The strategy uses the PNIEC through 2030 as a baseline and extrapolates the energy-environmental developments from that scenario to 2050. Establishing an 85–90% RES share in final consumption, an 84–87% reduction in emissions that contribute to climate change compared to 1990, and a 49% decrease in energy use compared to 2005 are some of the goals for the year 2050.
These national plans differ from EU directives in terms of their objectives and time frames because they were developed before their European counterparts. For instance, the 2019 Clean Energy Package's European standards are included in the PNIEC, but not the "Fit for 55" targets, which are more challenging. As a result, on June 14, 2022, the Ecological Transition Plan (PTE), which has more ambitious goals for Italy until 2030 and is in accordance with the "Fit for 55" European aim, was published in the Official Gazette.
The PTE estimates that by 2030, Italy must generate 72 percent of its energy from renewable sources, above the PNIEC's earlier objective of 60 percent. When combined, a 125–130 GW power generation capability and the reduction of CO2 emissions to 256 million tons from the current 381.

Table 2 - Comparison of current situation, 2030 targets set by PNIEC and PTE[32].

	Situazione attuale	Obiettivi 2030 – scenario PNIEC	Obiettivi 2030 – scenario PTE
% fonti di energia rinnovabili sul totale della generazione elettrica	41%	55%	72%
Capacità di generazione delle fonti di energia rinnovabili (GW)	60,6 GW	95,2 GW	125-130 GW
Emissioni di CO_2	381 Mln ton di CO_2	328 Mln ton di CO_2	256 Mln ton di CO_2

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Table 3 - A summary view of the most recent European and Italian energy policies [32].

Politiche energetiche europee		Politiche energetiche italiane
1. Clean energy for all Europeans package (2016)	→	1. Strategia energetica nazionale –SEN (2017)
2. EU energy strategy (2018)	→	2. Piano Nazionale Integrato Clima ed Energia – PNIEC (2019)
3. EU Long-Term strategy (2020)	→	3. Strategia italiana di lungo termine sulla riduzione delle emissioni dei gas a effetto serra (2020)
4. Green Deal europeo e Pacchetto «Fit for 55» (2021)	→	4. Piano per la transizione ecologica – PTE (2021)
5. REPowerEU plan (2022)	→	5. Aggiornamento del PNIEC e PTE (*da definire*)

1.7. Some laws at the proposal stage

1.7.1. The New Renewable Directive

The ambitious goal of raising the percentage of renewable energy in the final energy consumption of EU nations to 45 percent (from the present 32 percent) is one of the measures included in the revision of the Renewable Energy Directive, which is not yet approved (RED III). A regulation that has undergone several revisions to bring it into compliance with the ever-more-ambitious goals for reducing GHG emissions, which presently demand that the EU achieve climate neutrality by 2050. The Industry Committee had already presented the Parliament's viewpoint, which will now be negotiated with the EU Council to arrive at the final texts of two directives, Energy Efficiency and Renewables 2030, all of which are measures.

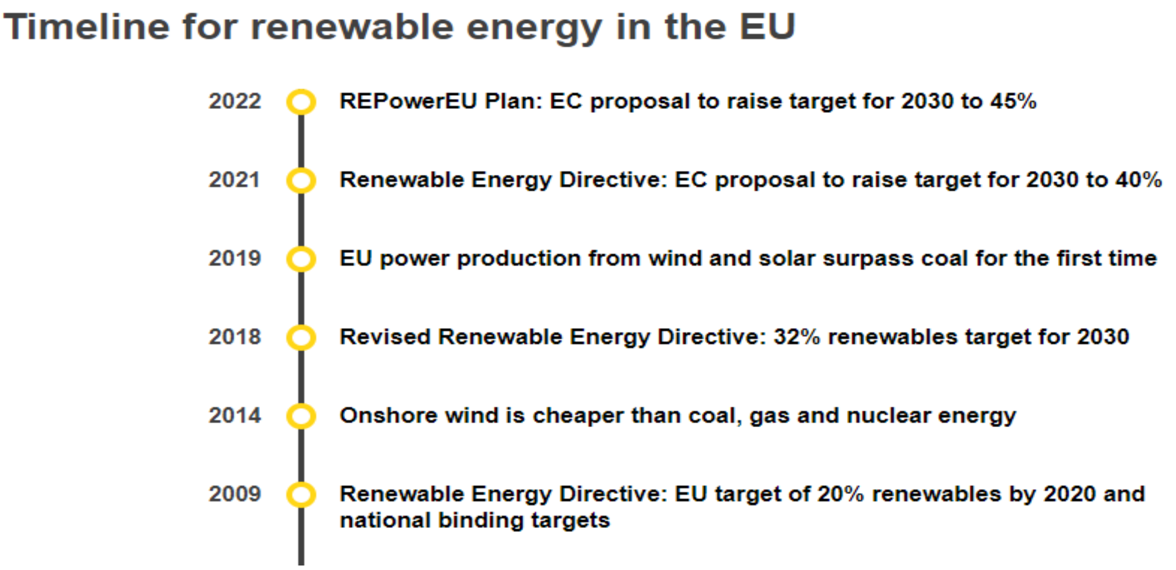


Figure 9 - Source: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en#timeline-for-renewable-energy-in-the-eu

1.7.2. The Hydrogen and Gas package

The European Green Deal lays out a plan for reducing GHG emissions while fostering a cutting-edge, resource-conserving economy. The Energy System Integration Strategy and the Hydrogen Strategy, which outline how to update the energy markets, including the decarbonization of the production and consumption of hydrogen and methane, are two of the initiatives included to achieve this goal.
Approximately 95% of the gaseous fuels used in the EU today are made up of natural gas (fossil methane). Gaseous fuels serve as an energy transporter as well as a crucial industrial feedstock and one of the sources of flexibility for an energy system that is increasingly dependent on fluctuating supply produced by renewable energy sources. The first set of recommendations to adapt the EU's climate, energy, transport, and taxation policies to reduce net GHG emissions by at least 55% by 2030, relative to 1990 levels, were agreed by the Commission on July 14, 2021. The demand for and production of renewable and low-carbon gases, such as hydrogen, are encouraged by this package.

The Hydrogen and gas markets decarbonisation package, issued in December 2021, is the review and amendment of the Gas Directive 2009/73/EC and Gas Regulation (EC) No 715/2009. It enables the market to decarbonize gas consumption and proposes the necessary governmental measures to assist the development of the best possible infrastructure and effective markets. It will eliminate obstacles to decarbonization and establish the prerequisites for a more affordable.
Three legislative measures are included in this package, which is part of the "Fit for 55" initiative to attain carbon neutrality in the EU by 2050:

- A proposal for an EU Directive on common rules for the internal markets for renewable energy, natural gas, and hydrogen (the "Proposed Gas and Hydrogen Directive")[33]
- A proposal to rewrite the EU Regulation on internal markets for renewable energy, natural gas, and hydrogen (the "Proposed Gas and Hydrogen Regulation");[34]
- A proposal to reduce methane emissions in the energy sector ("Proposed Methane Regulation").[35]

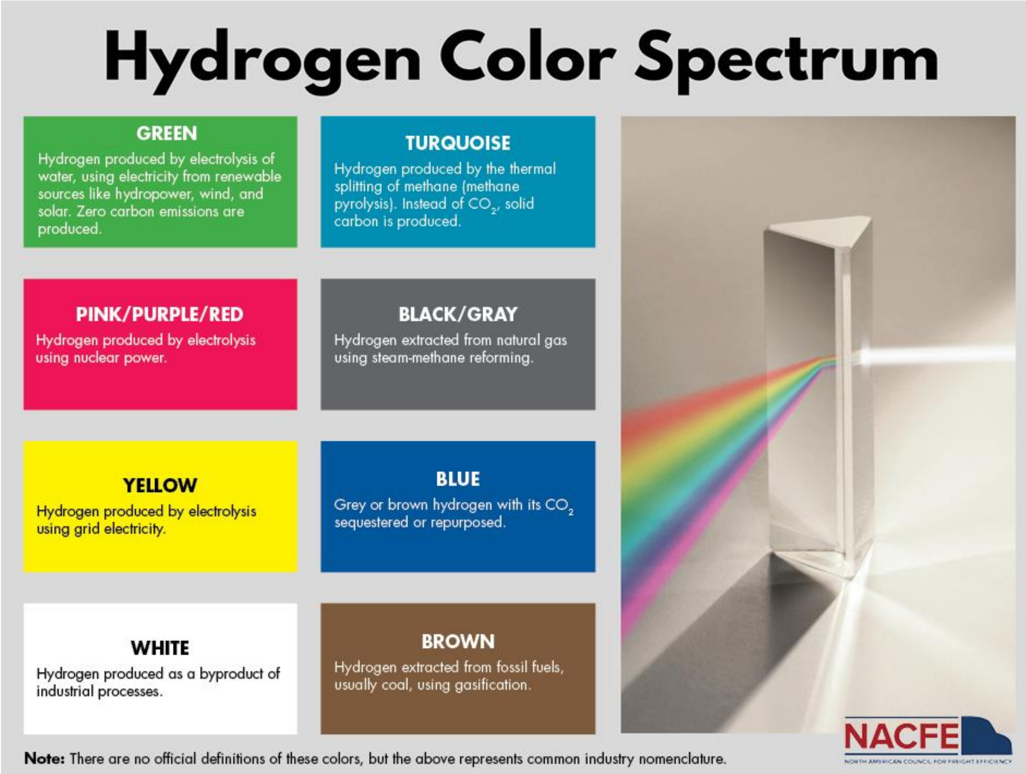
The package intends to make it easier to integrate renewable and low-carbon gases, including hydrogen, into the EU's energy infrastructure in accordance with the European Hydrogen Strategy. In order to encourage the use of hydrogen in industries and heavy transportation where electrification is not an option, the legislative proposals establish a dedicated hydrogen infrastructure and modify the regulatory framework for the gas market.

The proposed changes eliminate obstacles to the growth of the hydrogen market and infrastructure by establishing a level playing field based on European-wide standards. Additionally, they establish the ideal circumstances for the repurposing of natural gas infrastructure for hydrogen. This reduces expenses while also encouraging decarbonization.
In order to provide effective management of the European hydrogen network and to enable trade and supply of hydrogen across EU borders, the proposal establishes a European Network of Hydrogen Network Operators. Along with regulations for renewable hydrogen under the planned reform of the Renewable Energy Directive, it also includes a proposal for a vocabulary and certification system for hydrogen and low-carbon fuels.

1.8. Hydrogen issue

In this paper, the development of the hydrogen sector is considered, as seen, a key component in the process of decarbonization and diversification of energy sources, if produced in an environmentally sustainable manner.
A study and analysis of the hydrogen technology/regulatory framework has been proposed to define the point with respect to its applicability both in terms of technology and timing. A case study will help to understand how crucial some of the parameters used in the definition can become.
The current international energy regulatory framework does not give a definition, to date, of renewable and/or low-carbon or "green" hydrogen. The development of hydrogen infrastructure and markets in the EU has been hampered by this legal uncertainty. In order to solve this problem, we will explore into some legal proposals at the European level but also at the Italian level. As this paper develops, it will become clear that, at present, an empirical classification "of several colours" , as used today especially in the industrial world like the one proposed inTable 4, is neither in accordance with any standard nor completely adequate to regulatory purpose.
We will therefore begin, in the next chapter, to point out what are the differences between the various types of hydrogen production both in terms of the source of energy used to produce it and the materials used; and then go into an analysis of the current state of the legislation that gives us references on hydrogen.

Table 4 - Hypotetical colours of the hydrogen. Source: North American Council for Freight Efficiency (NACFE)



STATE OF THE ART

1 Hydrogen and decarbonization

Hydrogen is an energy carrier that has the great potential of behaving as an energy storage to couple time-varying energy supply and demand in order to ensure grid stability. For this reason, it can increase installed capacity from non-programmable renewable energy sources, such as PV and wind power generation [36].
Hydrogen can also be converted back into energy by stationary fuel cells. This adaptability greatly increases its possible applications and consumers.
Hydrogen can be used to decarbonize sectors for which there are currently no alternatives to fossil fuels from an economic point of view. One-third of global energy-related emissions are produced by this kind of sectors that are defined as "hard-to-abate". They include freight and long-haul trucking, steel industry, petrochemical industry, and mining industry [37].
Hydrogen can be used as a fuel for fuel cell electric vehicles (FCEVs) [38]. Large passenger cars, ships, trains, and commercial vehicles might all be decarbonized using fuel cell technology [39].
In Hydrogen traction, fuel cells vehicles do not emit CO_2 into the atmosphere or any other gas polluting the environment, but only water vapor as the "result" of electricity production.

1.1. What is hydrogen

1.1.1. Historical notes

The existence of hydrogen has long been known, although it was Paracelsus around the 16th century who first described a flammable gas produced by the reaction of sulfuric acid with iron. Later, in 1760, Henry Cavendish further studied the properties and preparation of hydrogen from water, and again, in 1783 Lavoisier gave this gas the name hydrogen, meaning "generator of water" [40].
Hydrogen is a key industrial gas. It has been used for inflating balloons for a very long time, but helium, which is somewhat heavier but inflammable, has replaced it due to its flammability, which led to several extremely terrible incidents (Akron, Hindenburg, etc.). In a huge variety of chemical processes, hydrogen is employed as a raw material. The synthesis of ammonia is the most significant example.

Hydrogen has long been used as a fuel in NASA's space programs [41]. Liquid hydrogen and oxygen are combined to obtain the fuel needed for the space shuttle and other rockets. The on-board fuel cells also, again combining hydrogen and oxygen, produce much of the required electricity. The only material discharged from the cells is pure water, used by the crew to quench their thirst.

The first oil crisis in the early 1970s sparked early interest in hydrogen as a fuel source. Many academics started to think about the crucial part that hydrogen may play in the energy sector [42]. Electrolysis may be used to make it quickly, after which it could be transported and stored in several ways. Hydrogen-based energy system of those years, however, was heavily linked to the availability of electricity, which acted as the only barrier to the development of a productive and competitive system. The belief that there were no other viable options for resolving the urgent energy crisis in the short term without the availability of reasonably priced electricity was further reinforced by the fact that methods for producing hydrogen other than electrolysis were dependent on the availability of fossil fuels. As a result, hydrogen energy research initiatives eventually came to an end.

During the 1980s, considerable progress was made in the study of technologies related to renewable resources and energy efficiency, such that research on highly efficient energy systems based on hydrogen and renewable sources appeared increasingly attractive. In particular, efforts were intensified to develop technologies that would strengthen the link between hydrogen and renewable sources in order to reduce, if not eliminate altogether, dependence on traditional fossil fuels . Achieving a fully hydrogen lifecycle-based system in fact presupposes the use of renewable energy sources for hydrogen production, since only oxygen and water would remain from such production processes, achieving so a zero environmental impact. Then, hydrogen can be stored and transported and in the end used in various possible applications.

Hydrogen is now considered an ideal energy source. It can be transported over huge distances via pipelines or by tanker ships, in most cases more economically and efficiently than electricity. It can be stored in:

- gaseous form (convenient for large-scale storage),
- in liquid form (convenient for air and land transport),
- or in metal hydride form (convenient for vehicle application or other relatively small-scale storage requirements).

Professor Frano Barbir, has written an introduction for World Conference on Hydrogen Energy [43], in which he points out that there are still widespread misconceptions about the development and use of hydrogen, which he instead identifies as not only a viable technology but also the key technology for complete decarbonization.

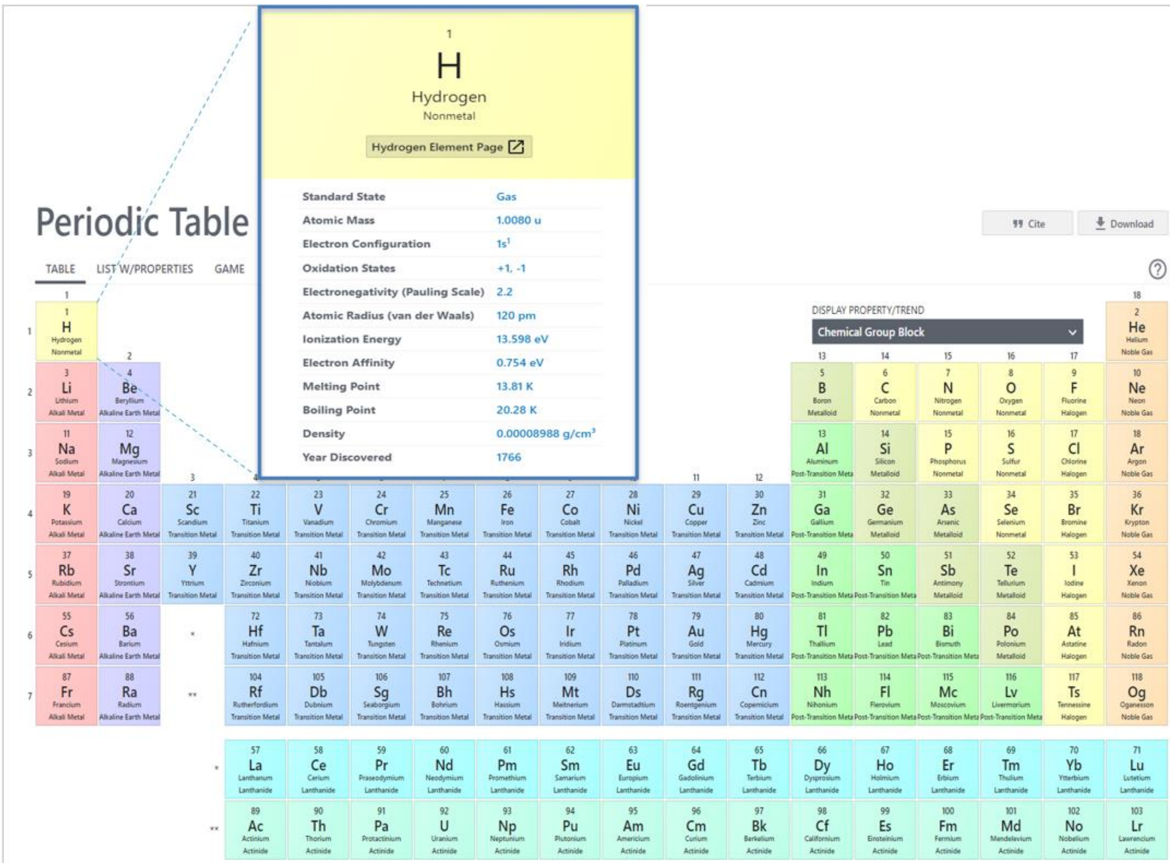
He reports that some people focus on one aspect, such as efficiency or storage size or perceived danger, and jump to conclusions without considering the bigger picture.

He then lists some most common misconceptions about hydrogen such as: hydrogen is (mainly) produced from fossil fuels (natural gas); there is no infrastructure for hydrogen; it is difficult to create a market for hydrogen fuel cell electric vehicles; it is inefficient to produce hydrogen and then convert it back to electricity, etc.. to which he punctually argues the not complete truth of the claims.
and closes by arguing, "*Hydrogen should not be judged by these individual properties, but by its ability to decarbonize those energy sectors that would otherwise be difficult to decarbonize*."

1.1.2. Chemical and thermodynamic properties

Hydrogen represents the most abundant element in the universe, as shown by spectral analysis of the light emitted by stars, which reveals that most of them consist mainly of hydrogen; for example, in the sun, it is present at about 90 %. It is one of the most widespread elements (0.9 percent by weight) in the Earth's crust, however very rare is hydrogen in its elemental state. It is found free in volcanic emanations, oil springs, fumaroles and in the atmosphere at heights above 100 km. On the other side, it is particularly abundant in the combined state: with oxygen it is present in water of which it constitutes 11.2 % by weight, combined with carbon, oxygen and some other elements it is one of the main constituents of the plant and animal world.
In the field of organic chemistry, millions of hydrogen-containing compounds are known, ranging from the simplest of hydrocarbons (methane) to giant carbohydrate proteins with a huge number of hydrogen atoms.
Hydrogen is at ambient temperature a colourless, odourless gas that is practically insoluble in water. After helium it is the most difficult gas to liquefy. It is a fair conductor of heat and electricity and is easily absorbed by certain metals. Generally inactive when cold, hydrogen gives rise to numerous chemical reactions when hot or in the presence of catalysts.

Table 5 - Periodic table of the elements: hydrogen. Source: https://pubchem.ncbi.nlm.nih.gov



Compared to natural gas or gasoline, hydrogen has a higher energy per unit of mass, making it a desirable fuel for transportation. On the other hand, has a lower energy per unit of volume, since it is the lightest element. In comparison to other fuels, this means that bigger volume of hydrogen must be transported to supply the same energy demands. This can be solved, for instance, by utilizing larger storage tanks and pipes with a quicker flow rate.

Table 6 - Physical properties of hydrogen [36]

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

1.2. Hydrogen demand

The demand of hydrogen has increased since 1975, and it is continually rising. Around 60% of this hydrogen is generated in "dedicated" facilities where it is their main output.

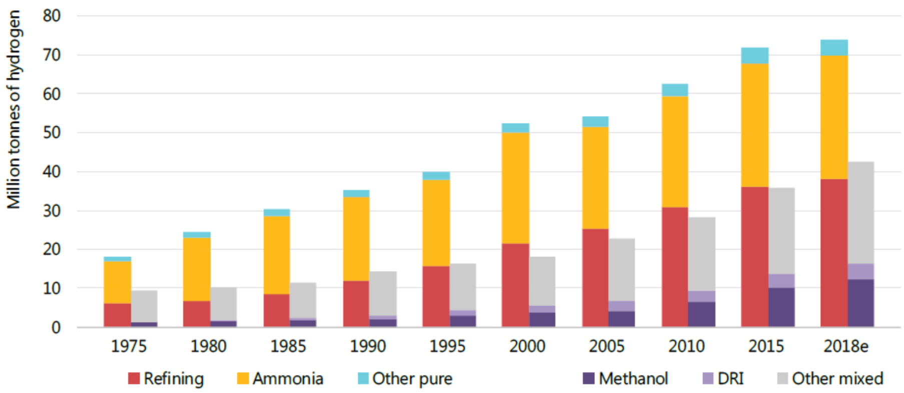


Figure 10 - Global annual demand for hydrogen since 1975 [36].

The annual production of pure hydrogen totals 70 million tonnes (MtH_2/y), which is nearly completely derived from fossil fuels. On the other hand, a third of the world's supply is "by product" hydrogen, which means that it originates from factories made primarily to make other products (different kinds of cleaning procedures are needed for this). Currently, less than 0.7% of hydrogen is produced from renewable energy sources or fossil fuel facilities that use CCUS technology, and this low percentage truly explains why hydrogen production is responsible for an emission level of 830 MtCO2/y [36]. In Italy, the hydrogen demand represents the 0.9% of the one of the entire world, around 0.448 Mt in 2011 [44].

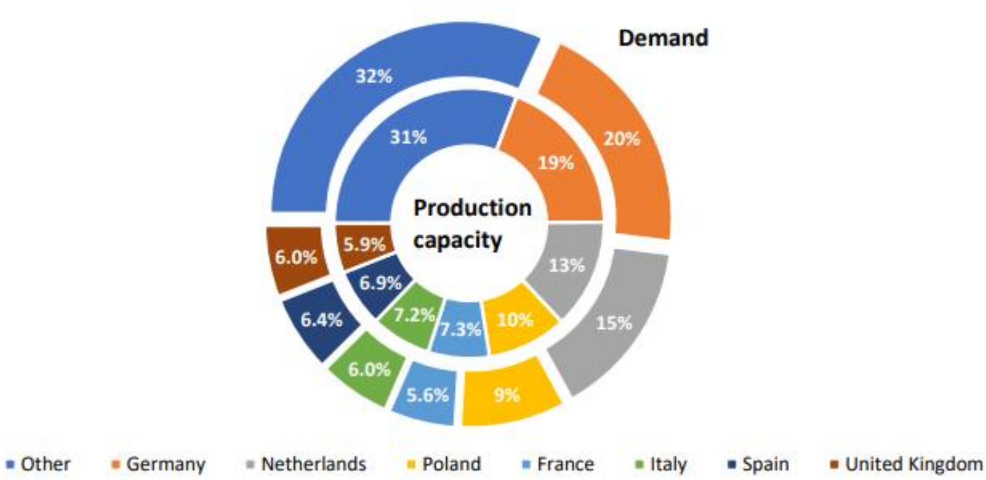


Figure 11- Total hydrogen production capacity and consumption by EU countries in 2020[45].

For Europe, the refining sector is responsible for 49% of total hydrogen demand (about 4.1 Mt), followed by the ammonia sector, which totals 31% of demand (about 2.6 Mt). In contrast, hydrogen demand for methanol production is equal to 5% of the total (about 0.4 Mt).

In terms of hydrogen consumption by country, Germany ranks first, accounting for 20% of the total European demand (about 1.67 Mt). It is followed by the Netherlands and Poland, with 15% and 9%, respectively, of total consumption of hydrogen.

In 2019, Italy represents the fifth largest European country by demand, amounting to about 0.58 Mt of H_2, corresponding to just under 7% of the European total.

More than 70% of Italy's domestic demand comes from the refining sector, while about 14% comes from the ammonia sector.

The remainder of the demand comes mainly from the other sectors of the chemical industry.[46]

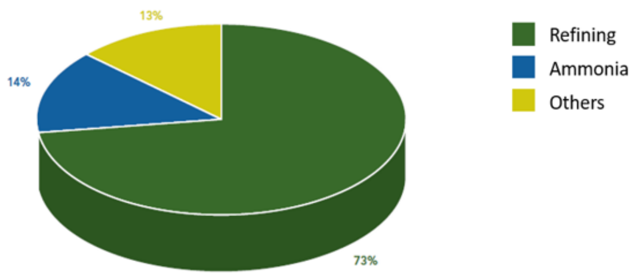


Figure 12 - Breakdown of hydrogen demand in Italy in 2019

1.3. Hydrogen production

1.3.1. Types of production facilities

In Europe, three sorts of hydrogen manufacturing facilities can be identified:

- Captive: are those that either create and deliver hydrogen to a single end customer or are designed for on-site hydrogen generation to fulfil the requirements of the facility.

- Merchant: designed to create hydrogen for sale to third parties, whether it is a by-product of other processes, an excess of captive production, or is produced solely for sale.

- By-product: hydrogen production occurs as a by-product of other processes, and is then sold to a nearby captive plant or used for internal activities.

1.3.2. Types of technologies

The strategic processes of hydrogen production, delivery, and storage allow hydrogen to contribute to a low-carbon future. Hydrogen is currently being produced in large quantities for use in industrial applications. Regulations governing hydrogen management reflect the fact that large-scale centralized generation of hydrogen from fossil fuels (coal, fuel oil, and natural gas) is a well-established industrial practice. Reforming is a process that makes hydrogen from fossil fuels, but it still emits CO_2 and other pollutants. It is a technology that works well, but it can only compete on a huge scale.

However, a variety of sustainable methods based on renewable energy sources can also be used to produce hydrogen, boosting so the level of penetration of renewables. In fact, hydrogen can be produced primarily through electrolysis, a process that only requires water and electricity; the latter one can be produced by renewable energy sources. Electrolysis is a system that is readily scaled up and that can also work well at smaller, more localized sites, such as those that produce sizable amounts of electricity from renewable sources or those where hydrogen is used as a fuel to power a fleet of zero-emission vehicles.

The main topic is that the sustainability of hydrogen depends especially on the way in which it is produced. Hydrogen can be extracted from fossil fuels (coal and natural gas) or can be produced starting from biomass or from water.

The major focus of development in recent years has been on renewable-based technology, particularly those for producing hydrogen using water. The development is not unexpected given that by 2050, the proportion of hydrogen produced from renewable sources, particularly water (electrolysis) and biomass, can climb from the present 5% and 30%, respectively. The IEA estimates that electrolysis may produce 79.72 Mt of hydrogen by 2030, compared to 55.56 Mt from fossil fuels with CCS, 13.43 Mt from fossil fuels with CCU, 52.78 Mt from fossil

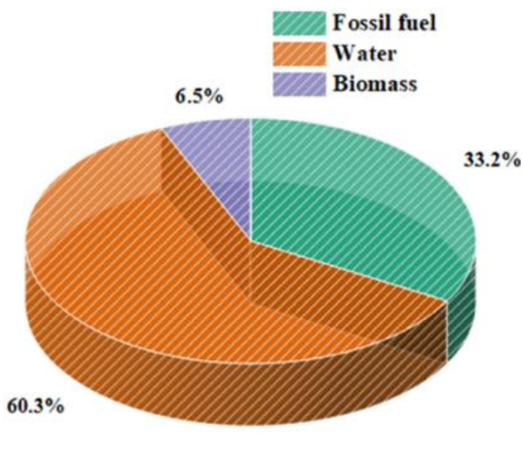


Figure 13 - Share of hydrogen production patents according to feedstock in the last five years.

fuels, and 10.67 Mt from refineries' by-products.[47]

It is useful to remember that the extraction of hydrogen from other substances is very energy-intensive.
Different process technologies can be used to produce hydrogen:

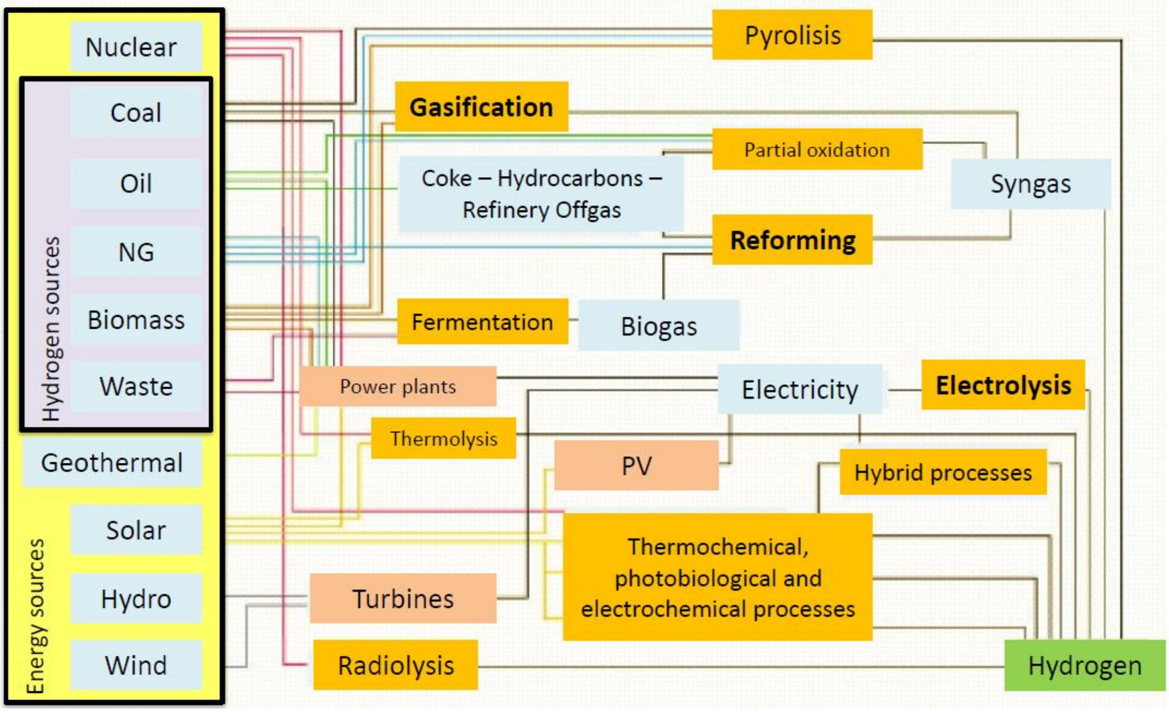


Figure 14 - Hydrogen Production patterns. [48]

The mainly conventional processes to produce hydrogen are:

- **Steam Methane Reforming** or **Methane Pyrolysis** produce hydrogen from natural gas
- **Gasification** processes convert solid fuel (such as coal or woody biomass) into hydrogen .
- **Electrolysis produces hydrogen** separating water into hydrogen and oxygen (power-to-gas).
- **Anaerobic digestion**, which produces hydrogen by breaking down wet material,.

The mainly source for hydrogen production is currently natural gas, especially with the so-called steam methane reforming process (SMR), that is the most widespread method, but the trend is now changing.

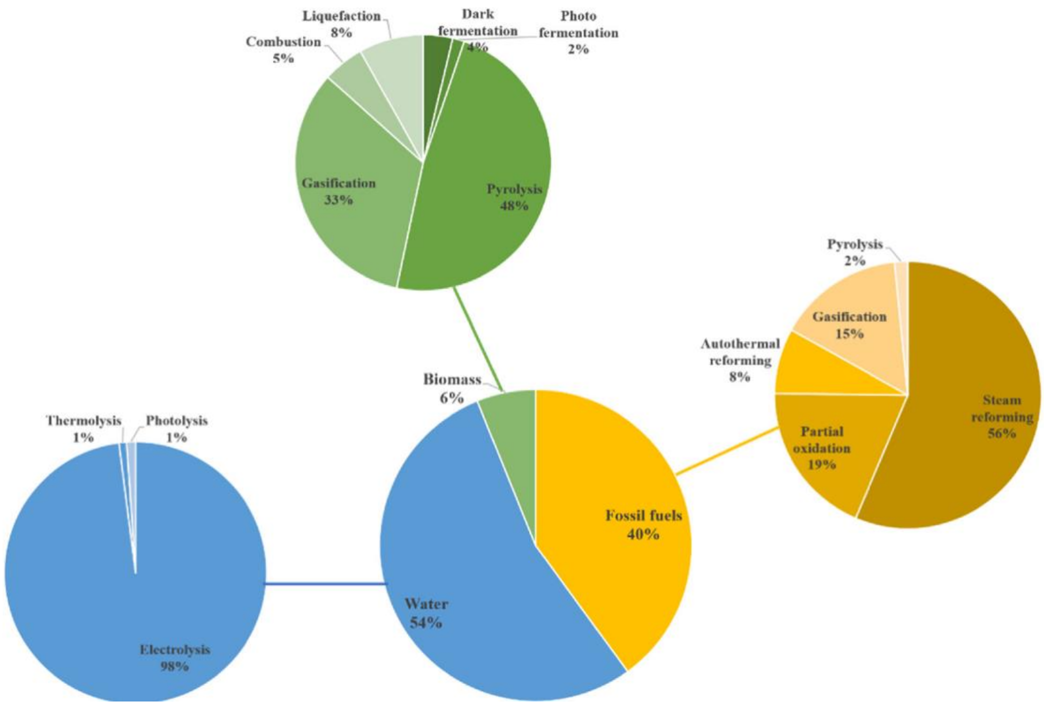


Figure 15 - Share of patents on specific technologies in the last five years.[47]

Other innovative technologies -not discussed but only listed- for hydrogen production are:

- Reforming Membrane reactors
- Chemical looping processes
- Methane decomposition
- Thermochemical cycles (Solar Thermolysis – Solar Thermochemical cycles TCC)
- Photo electrochemical cycles
- Photo thermochemical cycles

1.3.2.1. Steam methane reforming

The primary source for hydrogen production is currently natural gas, especially with the so-called steam methane reforming process (SMR), that is the most widespread technology. In steam-methane reforming, methane reacts with steam in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic, meaning that heat must be supplied to the process for the reaction to proceed.

Steam methane reforming: $CH_4 + H_2O + (heat) \rightarrow CO + 3H_2$

Subsequently, in what is called "water-gas shift reaction," the carbon monoxide and steam react using a catalyst to produce carbon dioxide and more hydrogen. The goal of this reaction is convert carbon monoxide (undesired products of SMR) into hydrogen, increasing the amount of useful products starting from a given quantity of methane. In a final process called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen.

Water-gas shift: $$CO + H_2O \rightarrow CO_2 + H_2 + (small\ amount\ of\ heat)$$

This kind of hydrogen production today generates significant CO_2 emissions: 10 tons of carbon dioxide per tons of hydrogen $\left(\frac{tCO_2}{tH_2}\right)$ produced from natural gas [49].

1.3.2.2. Reforming of Biomethane

Since huge amounts of organic waste are discharged due to human activity, which accelerates the production of greenhouse gases and changes the balance of the ecosystem, in order to achieve sustainable growth, the use of organic matter for energy production has increased significantly in recent years.
To produce biogas for energy, promoting so waste reduction and sustainability, the anaerobic digestion technique, which is widely used for organic matter, is currently applied to all plant and animal wastes (e.g., agricultural and municipal solid waste).
Because it has a low production cost and is more environmentally friendly than other biofuels, biogas can be considered a first-generation biofuel.

The direct reforming of biogas occurs by Dry Reforming of Methane, because biogas is rich in CH_4 and CO_2 (CH_4 is in excess in this case). Then the Partial Oxidation of Biomethane occurs by the addition of oxygen in a sufficient amount; finally to realize the Oxidative Reform of Biogas, an addition of O_2 to the biogas is needed to partially oxidize the excess of methane and leading to the Syngas (H_2/CO).

1.3.2.3. Biomass Gasification

Biomass is the fourth largest source of energy in the world, accounting for about 15% of the world's primary energy consumption and about 38% of the primary energy consumption in the developing countries. Biomass has the potential of accelerating the realization of hydrogen as a major fuel of the future. Since biomass is renewable and consumes atmospheric CO_2 during growth, it can have a small net CO_2 impact compared to fossil fuels.
There are two main routes for biomass-based hydrogen production:

- thermo-chemical route:

- pyrolysis: in which biomass is heated in absence of air. It can be taken bio-oil, char and tar after pyrolysis processes
- gasification: biomass is heated at high temperatures and disengage to combustible gas.
- Super Critical Water Gasification (SCWG)

- bio-chemical

Among of those, particular interest about, g**asification** that is a process that converts organic (biomass) or fossil based carbonaceous materials (coal) at high temperatures (>700°C), without combustion, and with a controlled amount of oxygen and/or steam, into carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2). The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen via a water-gas shift reaction, like for SMR. The final composition is then defined by a complex set of reactions. At low temperature the process yield a large amount of methane that is reduced at high temperature.
Adsorbers or special membranes can separate the hydrogen from this gas stream.
Air, steam or oxygen can be used as a gasification agent to increase energy value.
Another processes based on the same principle is **pyrolysis**. It involves a thermal decomposition without oxygen (400-800°C) that produces solid char, a liquid pyrolysis oil and a syngas.

Other systems for solid (or liquid) fuels conversion are based on biological processes (**fermentation, digestion**) that involve bacteria. The output is usually a biogas that can be purified or reformed.

1.3.2.4. Water Electrolysis

Electrolysis of water is also a process for producing hydrogen. The primary source is water, which is broken down into hydrogen and oxygen in an electrochemical cell.
Electrolysis is a process that takes place in a device called an electrolyser, which produces hydrogen (and oxygen) from water, previously treated. Electrolysis consumes electricity which can come from renewable sources. In the reaction, 9 kg of water and 44 kWh of electricity are required to produce 1 kg of H_2),.

Water Electrolysis: $H_2O \rightarrow H_2(g) + \frac{1}{2}O_2(g)$

Electrolysis, which was developed at the beginning of the 19th century, has long been the main method for producing hydrogen in the industrial sector. Since natural gas has increased over the past century, this manufacturing method has been replaced by the more advantageous steam methane reforming.
The relevance of water electrolysis is rising again. When it uses renewable power, it results a method to produce energy-sustainable hydrogen. The potential to link the

production of such a crucial technical gas to renewable energy seems to be quite attractive: it allows to renewable energy to be connected with heavy industry and transportation sectors, which have historically relied on fossil fuels.
Water electrolysis accounts for less than 0.01% of the world's total hydrogen production, and the hydrogen created in this way is mostly employed in sectors where high-purity hydrogen is required. Different types of architecture of the electrolytic cell may be categorized as Alkaline electrolysers, PEM electrolysers, and Solid Oxide (SO) electrolysers based on their electrolyte and charge carrier.

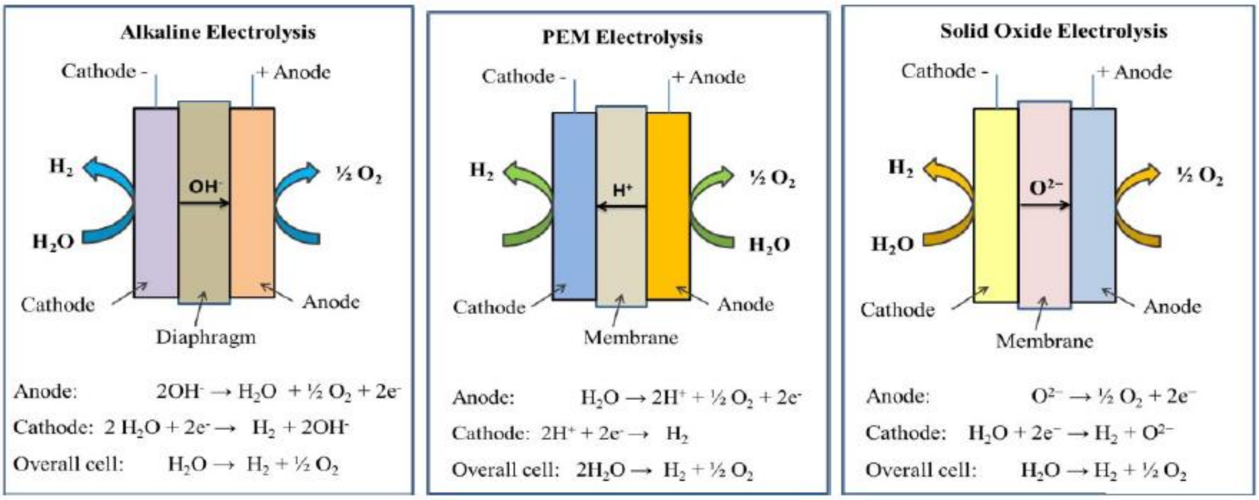


Figure 16- Alkaline Cell, PEM Cell, SO Cell

The temperature at which electrolysis is carried out has an important impact. Depending on it, there are two different families of electrolysis cells: [50]

- low-temperature cells – Alkaline, PEM – commercially available (T of operation between 50 and 80°C)
- high-temperature cells - solid oxide cells or SOEC - still under development (T of operation > 700°C)

Table 7 - Electrolysis: Technology today. [50].

	AEC	*PEMEC*	*SOEC*
Electrolyte	Alkaline water solution (liquid)	Polymeric membrane (solid)	Ceramic (solid)
Charge carrier	OH^-	H^+	O^{2-}
Operating temperature [°C]	60-90 °C	40-80 °C	650-1000 °C
Operating pressure [bar]	up to 30 bar_g	up to 30 bar_g	atmospheric
Current density	0.2-0.4 A/cm²	1-2 A/cm²	0.7-2.0 A/cm²
Load range	20-100 %	5-100 %	n/a
Electric efficiency (LHV)	40-65 %	50-70 %	>90 % (stack)
Maturity level	Commercial (mature)	Commercial (early)	Lab & demo (R&D)
Pros	Low investment cost	Compactness High H_2 purity	Non-noble metal catalysts
Cons	Noble metal catalysts Corrosive electrolyte	Noble metal catalysts	Not flexible, degradation

As explained before, the level of CO_2 emissions related to electrolysis systems depends on the way in which electricity is produced. Electrolysis cells supplied by a PV plant, for example, can produce hydrogen, without any kind of emissions.

1.3.3. Electrolysers

One in-depth study that it is useful to focus on is the field of electrolysers. Electrolysis of water is the preferred method for renewable hydrogen production. As will be seen below, the case study will approach a type of production that employs an electrolyser for hydrogen production.

The electrolyser consists of a direct current source and two electrodes coated with noble metal, separated by an electrolyte.

Individual cells and central system units make up electrolysers (plant balance). It is possible to customize hydrogen generation by fusing electrolytic cells and stacks.

1.3.3.1. Focus on electrolysers

Thera are four main technologies for electrolysis:

- the Alkaline electrolyser (ALK);
- the Anionic Exchange Membrane electrolyser (AEM);
- the Proton Exchange Membrane electrolyser (PEM);
- the Solid Oxide Electrolysis Cell Electrolyser (SOEC);

ALK and PEM cover almost the entire installed capacity today, while SOEC, AEM, are in the research phase and foresee future performances. The main characteristics of these different technologies are outlined in the following paragraphs. There are also some other technologies that are not yet widespread, and they are: Molten carbonate electrolyte and Microbial Electrolysis technologies. Let's see the main ones.

1.3.3.2. Alkaline electrolysers (ALK)

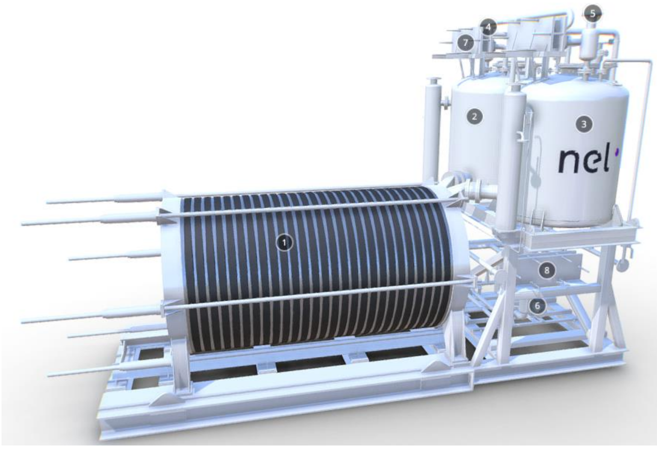


Figure 17 Alkaline Electrolyser. Source:

https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/

The alkaline cell, which offers a robust water electrolysis system utilized extensively for decades in the industrial sector, is the first technology that has been created and Alkaline electrolysis is in fact the most developed and most mature technology to date. The electrolyte or ionic conductor can be a liquid, such as a solution of potassium hydroxide, KOH .

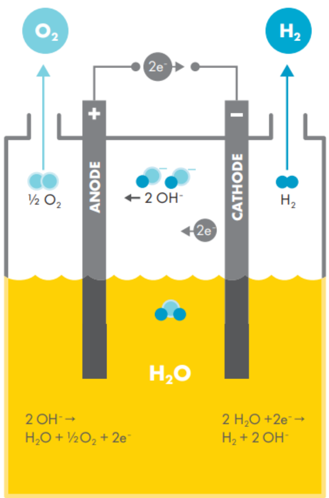


Figure 18 - An Alkaline Electrolyser working scheme[51].

In an alkaline electrolyzer (see Figure 18) the cathode (negative pole) loses electrons to aqueous solution (H_2O). Water is dissociated, leading to the formation of hydrogen (H_2) and hydroxide ions (OH^-). Charge carriers move in the electrolyte toward the anode. At the anode (positive pole), electrons are absorbed by negative OH^- anions. The OH^- anions are oxidized to form water and oxygen. Oxygen rises at the anode. A separator (cellulose or polymer) is placed between the positive and negative sides, as bubbles of H_2 and O_2 accumulate at the interface, causing some gas leakage in the wrong directions. This membrane allows only OH^- ions to pass through. Below are the reactions at cathode (a) and anode (b): [51]

(a) the hydrogen evolution reaction, occurring at the cathode

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

(b) the oxygen evolution reaction, occurring at the anode

$$2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^-$$

The alkaline environment is not very degrading to cell components and allows the use of Ni-based catalysts to promote the reaction, as well as inexpensive materials for current collectors (mainly steel). For this reason, and because of the maturity of the technology, alkaline electrolyzers are the cheapest on the market.
The efficiency of electrolysis is determined by the amount of electricity used to produce an amount of hydrogen. Hydrogen is produced with an efficiency of 55-65% on LHV basis [52]. The thermodynamic efficiency of an electrolyser is defined as:

$$\eta_{el}^{th} = FU \cdot \frac{\frac{LHV_{H_2}}{2F}}{\Delta V}$$

Where: LHV_{H2} is the low heating value of hydrogen

F is the Faraday constant

ΔV is the voltage applied across the cell

FU is the Fuel utilization, which accounts for that part of the produced H_2 by the cell that is lost due to the recombination of H_2 and O_2 inside the system. For this technology FU ≅ 0:96-0:98, which means that 2 to 4% of the H_2 is not actually useful [52].

The mixing of H_2 and O_2 after they have generated inside the cell is known as crossover. The fundamental issue with the alkaline cell is "crossover", which accounts for the portion of H_2 that cannot be utilised.
As a result of the concentration differential between H_2 and O_2 inside the electrolytic cell, it is mostly connected to diffusion. The two gases can combine, which can result in a loss of energy and the generation of hydrogen as well as the formation of an explosive combination and serious safety concerns. The cell is made with a big space between the two electrodes to reduce the amount of H_2 and O_2 bubbles near the separator and to limit mixing between the two gases. The OH^- ions must travel a greater distance, however, which results in greater ion transport losses and ohmic losses.
This is also why the alkaline electrolyzer is the bulkiest of all the electrolyzers marketed, with a power density 25% lower than the others.
All of these characteristics are a result of the electrolyser's design: to produce hydrogen, bubbles of H_2 and O_2 must grow near to the catalyst layer, which leads to a

buildup of these bubbles in the system's active region. Such bubbles enhance the system's mass transport losses by obstructing the flow of OH^- ions. Because of this, the alkaline cell's current and power are both capped at 0.5. Low cell efficiency and the requirement for large, costly to transport stacks result from a lower current corresponding to a larger voltage across the cell. In reality, one of the main causes of the alkaline electrolysers' CAPEX is stack mobility.
Alkaline electrolysis, whose main shortcomings we have seen above, to be low efficiency and low current intensity, also has other problems:

- Hydrogen-powered vehicles require extremely pure hydrogen (99.97%, hydrogen fuel quality specifications listed in ISO 14687); this process assures of 99.7% -99.9%, limited by crossover and by the presence of electrolyte traces inside the product gasses.
- the partial load operation of the cell. In order to prevent the creation of an exploding mixture of H_2 and O_2, the maximum amount of H_2 that can end up inside the O_2 stream is 4%.

Despite these issues, being the first electrolyser that has been commercially implemented, the alkaline technology has a high lifetime of 60000 to 100000 h.The use of low-cost components and the long lifetime make this technology the most widespread worldwide for H_2 production.

1.3.3.3. Anionic exchange membrane electrolysers (AEM)

Another technology developed is the anion exchange membrane (AEM) cell.
The reactions that take place in the electrodes are the same as in conventional alkaline cells, but a "zero gap" configuration has been created for the alkaline technology to overcome the issues related to ALK.
The design of the cell is characterized keeping an alkaline electrolyte's employment; direct contact is made between two porous electrodes and a tiny membrane that lets OH^- ions flow through. This cell is referred to as an electrolytic anion exchange (AEM) cell since it uses a membrane. Better separation of the two sides of the cell, less gas mixing, and reduced ion transport losses are all made possible by AEM technology (since the two electrodes are placed much closer to each other).

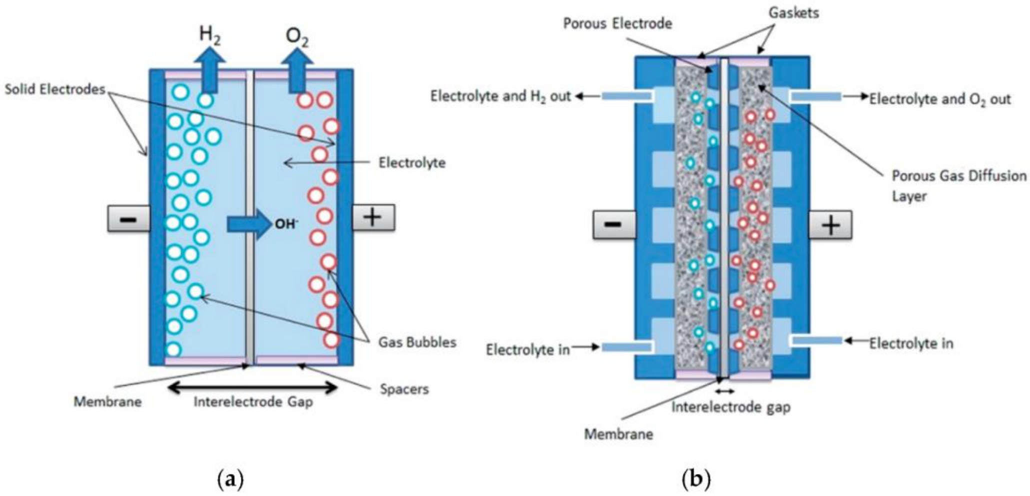


Figure 19 - Representation of the traditional alkaline cell a) and b) of the zero-gap alkaline technology [53]

AEM, the most recent technology to enter the electrolysis market in chronological order, was created with the goal of fusing the alkaline cell's cost-effectiveness with the PEM cells' enhanced performance. In reality, the design of an AEM cell may be seen as a modification of PEM technology, with the key distinction that it relies on the transport of hydroxide ions (OH^-) rather than protons (H^+), as well as a major enhancement of the strength and impermeability of alkaline cell separators.
The AEM technology, which is affordable, highly effective, space-efficient, and highly reactive, satisfies all requirements for the implementation of power-to-gas technologies in the future (i.e., excellent for coupling with renewable sources). Although this technology has a lot of potential, its membrane is not yet robust and developed scientifically. This has an impact on the electrolyzer's usable life, which is just 500–10,000 operating hours. There aren't many AEM electrolyzers on the market right now; the most of them are in the kW range.

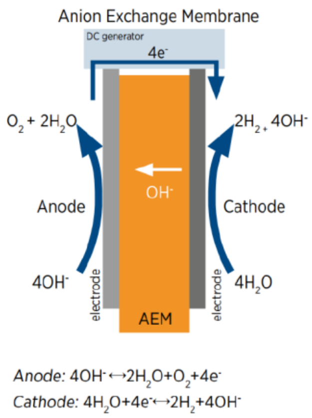


Figure 20 - Working scheme of the AEM

1.3.3.4. Proton exchange membrane electrolysers (PEM)

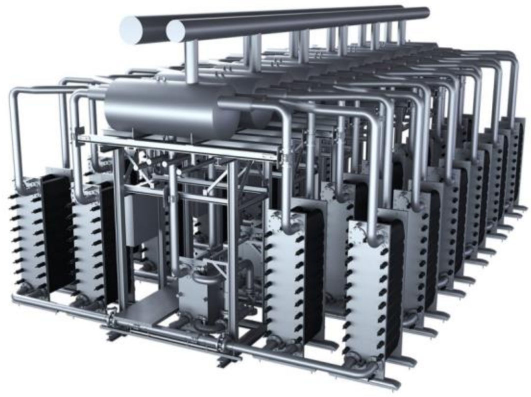


Figure 21 Proton Exchange Membrane (PEM). Source: https://www.agvenergy.com/green-hydrogen/

The second most used method for generating hydrogen from electrolysis is proton exchange membrane electrolysis (PEM). In order to address the shortcomings of ALK technology, General Electric introduced them in the latter part of the 20th century.[54] It has variable operating characteristics and is perfect for coupling to intermittent energy sources like renewables because of its quick dynamics and large part-load range (10–100%). The anion-exchange membrane's design is very similar to this one. The basic idea is the same—this time inside an acid electrolyte—two porous electrodes are positioned in close proximity to one another.[52]
H+ ions specifically travel from the anode to the cathode to facilitate the reaction. There are two primary components to the electrolysis process.

- the reaction at the cathode (reduction)

$$2H^+ + 2e^- \rightarrow H_2$$

- the oxygen reaction, at the anode (oxidation)

$$H_2O \rightarrow 2H^+ + \frac{1}{2}\,O_2 + \,2e^-$$

This kind of electrolytic cell must be made using expensive components since the atmosphere is so acidic. Platinum applied to carbon (Pt/C), the most effective catalyst for accelerating the hydrogen evolution process, is utilized at the cathode. Iridium or ruthenium are employed at the anodes (IrO_x or RuO_x). Titanium is used to make both the separator plate and the current collector. These materials are substantially more expensive than those required for the alkaline cell. On LHV, the PEM cell's efficiency rises to 60% to 70%.
Low transport losses are guaranteed by this sort of cell's more compact construction and the H^+ ion's lower flow resistance as compared to OH^-. While an increase in current density of more than 0.5 A/cm^2 for the alkaline cell would induce more bubble

formation and an increase in the potential difference required to operate the system, for the PEM electrolyzer the limiting current density can reach a value of 2 A/cm^2 .
The V across the cell is lower than it is in alkaline electrolyzers due to the higher current density, which enables higher stack efficiency. Better separation between the H_2 and O_2 sides of the cell is made possible by the membrane's existence rather than a separator, which reduces crossover and raises fuel consumption to 0.98 to 0.99. The collected gas is completely free of electrolyte, with purity values exceeding 99.99%. Finally, PEM electrolyzers create pressurized hydrogen up to 100 bar and ambient pressure oxygen concurrently while allowing pressurization of only one side of the electrolytic cell. Another accomplishment made possible by the membrane design is this one.
As alkaline cells, these cells have a lifespan of between 60000 and 90000 hours today. They lose less performance and take up a fourth less area than alkaline electrolyzers. Given the usage of platinum and iridium in these sorts of electrolyzers, their particular cost is significantly greater than other commercially available cells, which may restrict the technology's capacity to scale. The current level of iridium production might sustain up to 7 GW of annual electrolyzer output.

1.3.3.5. Solid Oxide Electrolyser Cells (SOEC)

Figure 22 Solid Oxide Electrolyser. Source: https://www.h2epower.net/solid-oxide-electrolyser-cell/

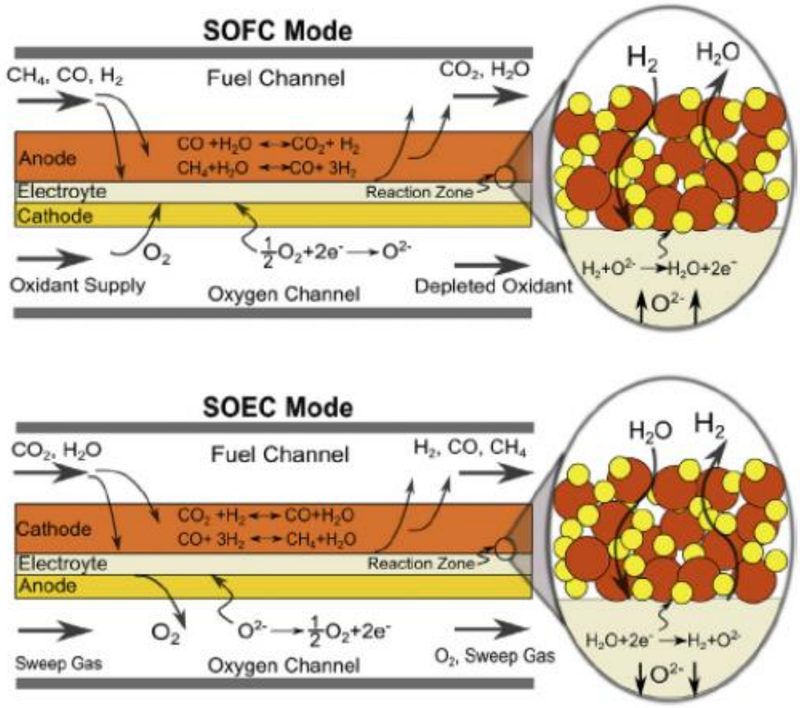


Figure 23 - Reversible SOEC Cell.[50]

In a solid oxide electrolyzer (SOEC), low cost Nickel electrodes are used in combination with the electrolyte. The typical working temperature of SOEC is in the range of 700 – 850°C with the pressure at 1 bar. This cell achieves a very low specific consumption of 40 kWh / kg, while it is around 50 kWh/kg for other technologies. SOEC can be integrated with industrial processes in which there is the generation of thermal energy as a by-product, for example the synthesis of fuels. Operation is based on a solid oxide ceramic electrolyte, permeable to the O_2-ion, and uses a high temperature steam inlet to replace water. SOEC is not yet commercialized due to stack degradation and its short useful life caused by high operating temperatures.

This electrolysis method has the characteristic of being entirely reversible; in fact, SOECs may function as fuel cells, turning hydrogen into electricity and water at a nominal power of 25% less than electrolysis. There are currently few MW-scale projects using this technology, which is still on the kW scale. However, it undergoes extensive testing in the lab to ensure that it lives up to its claims of great energy efficiency and adaptability for usage in industrial settings.

1.3.3.6. Technologies comparison

In the Figure 24 is represented a comparison made with respect to some characteristics of the examined electrolyzers: efficiency, OPEX, output pressure, minimum load, compactness of the system, best cost for the electrolyte, and water quality.

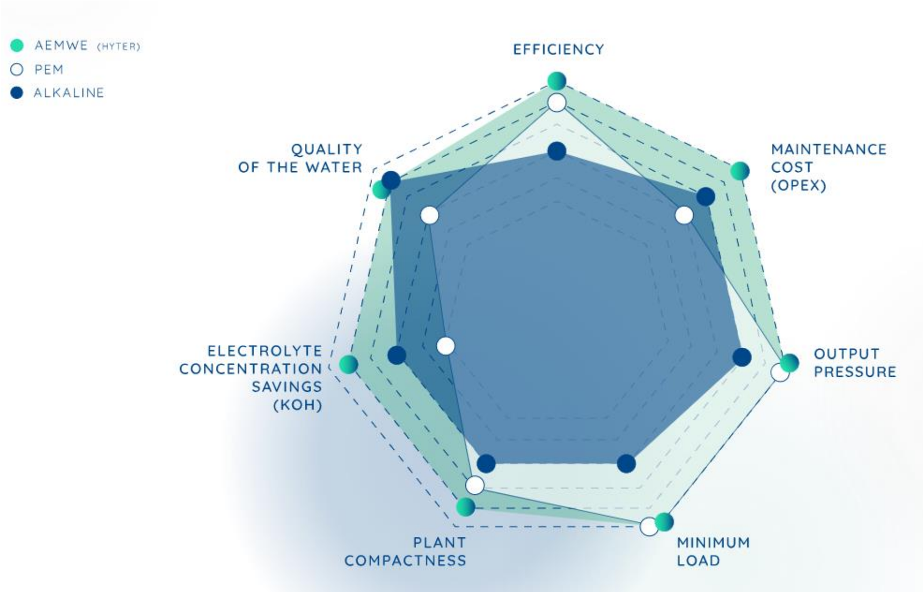


Figure 24 - Feauturs of electrolysers: comparison. Source: Hyter[55]

1.4. The post-production treatment of hydrogen

Hydrogen needs to be further purified after production. Impurities can prevent machinery from storing, dispensing, or using hydrogen properly.
Depending on the impurities present, a variety of methods are available for hydrogen purification, which is a crucial component of hydrogen distribution.
Impurities have different effects depending on their physio-chemical features and on the equipment being used. Inert impurities like nitrogen are often less hazardous than reactive species like hydrogen sulphide, and hydrogen boilers can tolerate larger concentrations of impurities than a car, which uses polymer electrolyte membrane fuel cell (PEMFC).
Standards that specify in-depth criteria for fuel purity for certain purposes have been produced. Depending on the purpose, the international standard ISO 14687:2019 provides the maximum allowable amounts for several important contaminants. Many governments are adopting this norm into their laws. For instance, the ISO 14687-2 technical criteria for hydrogen purity must be respected by hydrogen refuelling sites, in order to comply with the Directive 2014/94/EU [56] about the implementation of alternative fuels infrastructure in Europe.
Impurities in hydrogen might exist depending on the feedstock and manufacturing method. Water and trace oxygen are frequently present in the hydrogen produced by electrolysis, and these components must typically be removed before use.
Various co-products and residual reactants that are present in the crude hydrogen-based gases created by steam reforming must be separated.
In hydrogen produced by water electrolysis, moisture and traces of oxygen are present.

Naturally, the price of hydrogen varies according to the needed degree of purity, and the size of the equipment.

1.5. Hydrogen compression

Among regularly used fuels, hydrogen has the lowest volumetric energy density. Hydrogen must thus be compressed in order to improve its energy density [57]. The following are techniques for compressing hydrogen:

- Gas cylinder compression;
- cryogenic tank liquefaction;
- Storing in alloys of metal hydrides.

Figure 25 - Hydrogen compressor. Source: http://www.idromeccanica.it/compressors/

Compression is the most extensively used way to store hydrogen since it is the most typical solution . Mechanical compressors come in a variety of kinds, such as reciprocating piston compressors, linear compressors, diaphragm compressors, etc.

1.6. Hydrogen supply chain

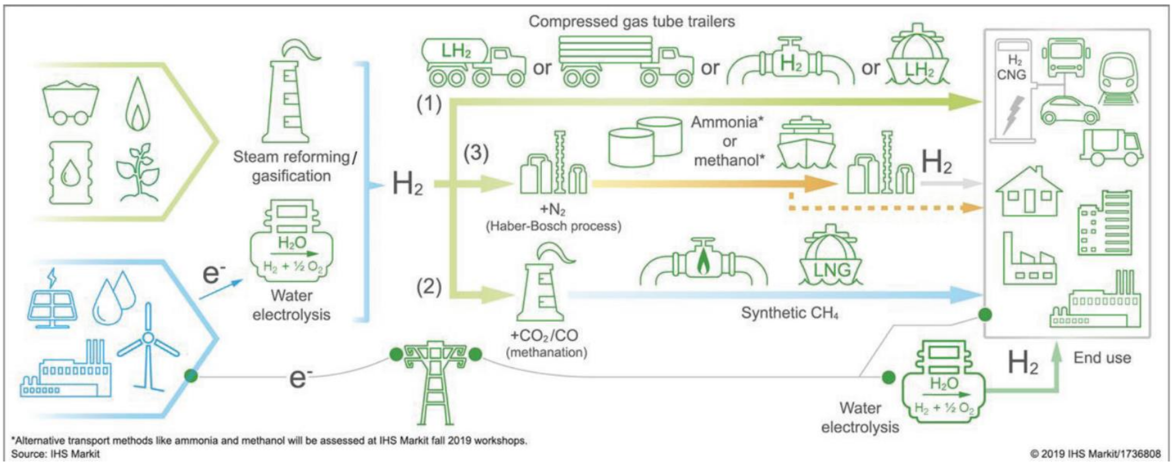


Figure 26 – Hydrogen Supply Chain. Source: IHS Markit.[58]

It has been seen that there are many hydrogen production solutions that differ in terms of cost, technologies involved, and emission levels. Based on the hydrogen production technologies and their emission levels, it is possible to distinguish between different hydrogen supply chains.

Processes such as:

- SMR or coal gasification produce hydrogen by emitting CO_2 into the atmosphere. However, these plants can be equipped with CCUS systems, which prevents CO_2 from reaching the atmosphere: the CO_2 is separated and stored underground (CCS, Carbon Capture and Storage), for example, or used directly (CCU, Carbon Capture and Utilisation) in other industrial applications.
- Through the electrolysis of water and the use of electricity from renewable sources there is a hydrogen production with no or low emissions. These emissions must be taken into account when choosing the most appropriate production methods that meet increasingly stringent environmental and climate goals, considering also the economic sustainability of the project itself.

As we have already mentioned, flexibility is one of the main advantages of hydrogen as an energy carrier. The approach in which electricity is transformed into hydrogen through electrolysis, stored and re-electrified by means of a fuel cell when needed to balance electricity supply and demand is called Power to Power (P2P). However, this is not the only possible solution. There is the Power to Gas, in which electricity is converted into hydrogen through electrolysis and then blended into the natural gas grid or converted into synthetic methane. Besides, hydrogen can power FCEVs in the transportation sector or can be used directly as a feedstock, such as in the chemical or refining industry. However, it is important to consider that all energy carriers have losses during their conversion, production and utilization processes, that are worth paying attention to.

1.7. Storage

Storing hydrogen as compressed gas is the most often used method.

There are different storage methods for hydrogen that have different requirements regarding the purity in the storage process.

The main implemented process in industry is the Pressure swing adsorption (PSA), sometimes in a combination with other processes. PSA processes rely on the fact that under pressure gases tend to be attracted to solid surfaces; this is the adsorbing process. Higher the pressure, more gas is adsorbed; when the pressure is reduced, the gas is released, or desorbed. PSA processes can be used to separate gases in a mixture because different gases tend to be attracted to different solid surfaces more or less strongly. If a gas mixture such as hydrogen with several impurities is passed under pressure through a vessel containing an adsorbent bed that attracts CO, N_2, O_2, nearly pure hydrogen will leave the adsorber bed. When the bed reaches the end of its capacity, it can be regenerated by reducing the pressure, thereby releasing the adsorbed molecules. In this way, it is then ready for another cycle. Typical adsorbents are activated carbon, silica gel, alumina, and zeolites.

To understand the behaviour of hydrogen during compression it is important to have a look on real gasses law and on the pressure - density diagram for hydrogen.

For six temperatures the curves are shown below. At lower pressures, the relation is more or less directly proportional. At higher pressures, the density does not increase in the same ratio. Doubling the pressure at 298 K (from 100 to 200 MPa) results in the increase of density only by a factor of 1.4.

Van der Waals equation $$\left(p + \frac{an^2}{V^2}\right)(V - n \times b) = nRT$$

Table 8 - Properties of compressed hydrogen and gasoline[50]

Properties @ 293.15 K	Compressed hydrogen	Compressed natural gas	Gasoline
Upper heating value (MJ kg^{-1})	143	55	44
Lower heating value (MJ kg^{-1})	120	50	41
Density (kg m^{-3}) @ 100 kPa	49.939		720–770 @ 0.1 MPa
Density (kg m^{-3}) @ 70 MPa	39.693		
Density (kg m^{-3}) @ 35 MPa	23.651		
Density (kg m^{-3}) @ 20 MPa	14.707	162	
Volumetric energy density (MJ L^{-1}) @ 100 kPa	7.14		30.5 @ 0.1 MPa
Volumetric energy density (MJ L^{-1}) @ 70 MPa	5.68		
Volumetric energy density (MJ L^{-1}) @ 35 MPa	3.38		
Volumetric energy density (MJ L^{-1}) @ 20 MPa	2.1	8.8	

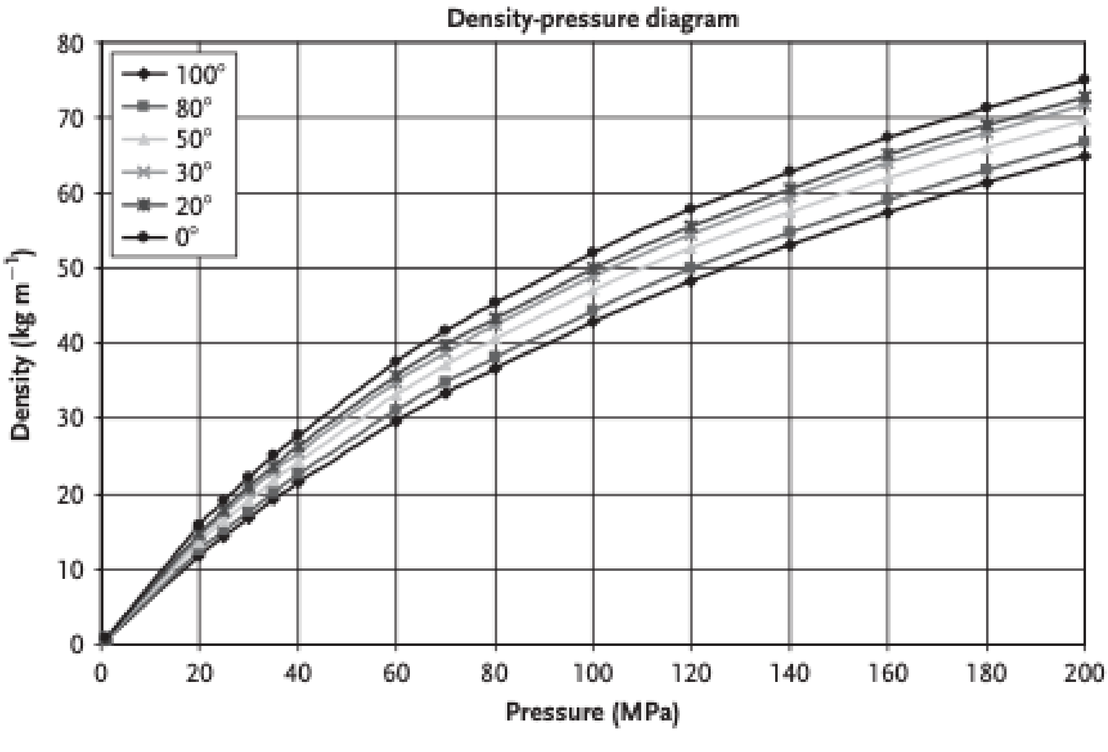


Figure 27 Density of compressed hydrogen as function of the pressure for different temperatures

1.8. Power-to-Hydrogen

A broader category of technologies, known as power-to-gas (P2G), includes the electrolysis of renewable (non-programmable) energy sources to produce hydrogen with no or minimal carbon emissions. In general, the broad category of technologies known as "power-to-gas" includes those that enable the conversion and storage of excess renewable electricity into gaseous fuels such as hydrogen or methane. These systems are well suited to control the fluctuations of non-programmable renewable energy sources, providing them with more balanced power generation due to their long-term gas storage capabilities. Power-to-gas can be the key to avoiding grid curtailments and imbalances and reducing the need to build the power grid infrastructure in a global context where renewables need to grow rapidly.

With this model, the cost of excess renewable energy could then go to zero and consequently bring benefits on the cost of H2, which would then be highly competitive in trend.

In terms of end-use applications, the hydrogen generated can be sold to industrial customers, used as a storage medium that can later be converted back into energy, or used for transportation, as in fuel cell electric vehicles (FCEVs).

1.9. Types of hydrogen

It is now possible to remark again the strategic processes of hydrogen production, delivery, and storage allow hydrogen to contribute to a low-carbon future. Hydrogen is currently being produced in large quantities for use in industrial applications.

As it has been pointed out, hydrogen can be produced from many sorts of energy sources, including coal, oil, natural gas, biomass, renewable energy sources, and nuclear, using a wide range of technologies (reforming, gasification, electrolysis, pyrolysis, water splitting and many others).

Each production pathway can have a distinct environmental impact because of the many energy sources that can be used, and this affects hydrogen's potential to reduce CO_2 emissions.

IEA Global Energy Review [59] states: "*In recent years, colours have been used to refer to different hydrogen production routes (e.g. green for hydrogen from renewables and blue for production from natural gas with carbon capture, utilisation and storage [CCUS]), and specialised terms currently under discussion include "safe", "sustainable", "low-carbon" and "clean".* ***There is no international agreement on the use of these terms as yet, nor have their meanings in this context been clearly defined.***"

2 Hydrogen Regulations

2.1. Global framework of strategies

European Commission and other 25 countries have launched strategies that use hydrogen as a clean energy carrier in their plans for the energy transition. Europe has the majority of the strategies.

National strategies presently cover just 17% of emissions, while China and developing economies collectively account for around 40%.

The development plan for the Chinese hydrogen industry stands out amid recent statements. China, which is responsible for 30% of the world's hydrogen demand, might have a significant effect on the growth of hydrogen projects in the next years. The aims of the plan are more time-bound (2025) than those of most previous national programs. An objective of the Chinese approach is to produce 100–200 kt of hydrogen (kt H_2) from renewable sources.

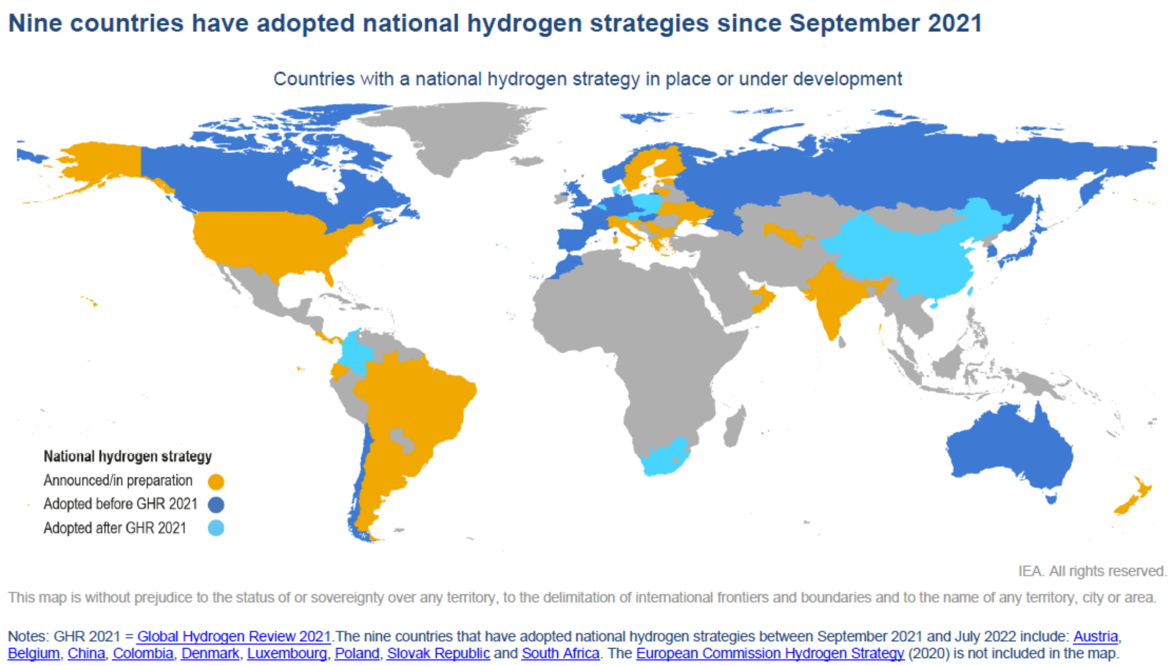


Figure 28 - Hydrogen strategies adoption map. Source: Global hydrogen review 2022, IEA.

A national hydrogen strategy is being developed by more than 20 governments in addition to the ones that have previously been accepted. Italy has published guidelines and is in the process of defining the actual strategy; other governments have announced plans to revise their hydrogen strategies, such as Germany, which is expected to publish a revised strategy by the end 2022. Also India and the United States are expected to publish their strategies by the end of 2022.

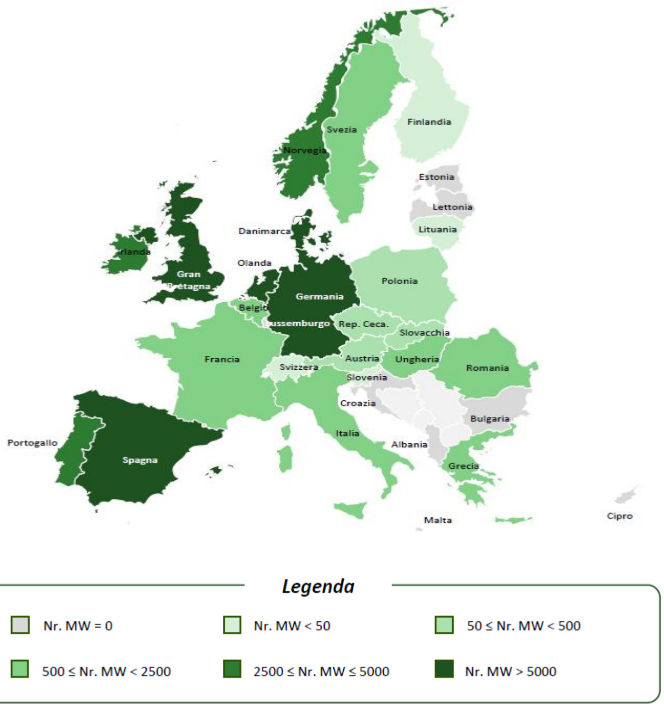


Figure 29 - Number of plants in MW planned in Europe.

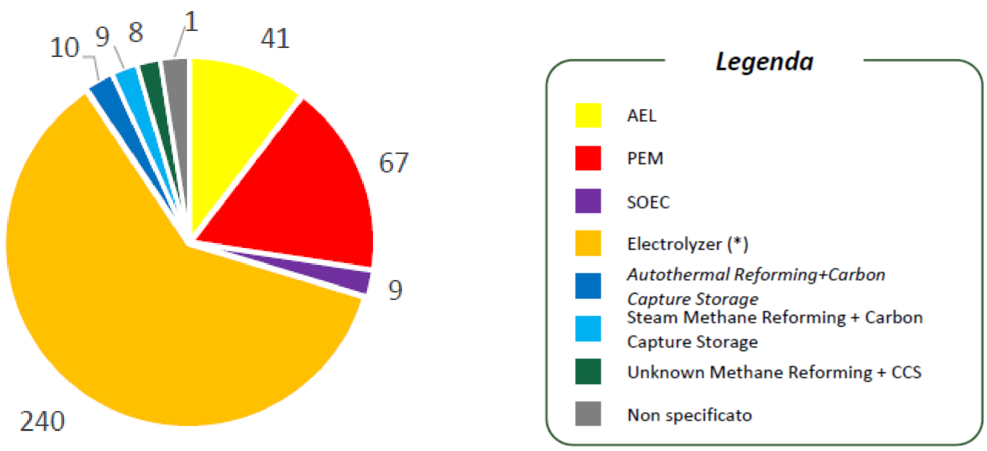


Figure 30- Distribution of H_2 production technologies by number of projects. Source: "Lo Sviluppo di un mercato per l'idrogeno: tra installazioni annunciate e necessità di nuove installazioni FER." Source: Energy & Strategy – Politecnico di Milano, 2022.

2.2. The European Hydrogen Strategy

The European Commission, through its **Communication** (atypical, not-legal act [60]) "A Hydrogen Strategy for a climate-neutral Europe" on July 2020 presented a new policy programme aims to give a boost to clean hydrogen production in Europe.
A vision for the development of a European hydrogen ecosystem, spanning research and innovation, scaling up production, and infrastructure to an international level,

was presented in the EU's adoption of its hydrogen plan in 2020. The EU's goal for integrating the energy system includes hydrogen as a significant component.

The plan examined how, in line with the European Green Deal, generating and consuming renewable hydrogen may contribute to the EU economy's cost-effective decarbonization.

A presentation sheet prepared by the committee states the is necessary encourage the production of clean, renewable hydrogen in order to decarbonize the European economy.

Wind and solar energy should be primarily used for this imperative. However, in the near and medium future, additional low-carbon hydrogen sources are required to significantly advance the establishment of a market and enable the quick reduction of emissions from current hydrogen production.

It is the responsibility of the Commission to strive toward the introduction of thorough language and certification to describe renewable and other types of hydrogen. The EU taxonomy for sustainable investments will be followed, and ECE will be based on lifecycle carbon emissions, rooted on current climate and energy laws.

In line with the above, the different ways of producing hydrogen, their GHG emissions, their relative competitiveness, and depending on the technology and energy source used, some types of hydrogen are defined as follows in the communication:

- *'**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*[19].
- *'**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*[20]. *Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass*[21]*, if in compliance with sustainability requirements.*
- *'**Clean hydrogen'** refers to renewable hydrogen.*

The goal of the European Strategy, which is developed in three successive time phases, is to generate the emergence, development and diffusion of the hydrogen market and the achievement of total hydrogen production for end uses through green hydrogen by 2050.

The strategy thus aims to foster the emergence and development of the hydrogen supply chain, starting from its production through electrolysers, through transportation and storage, to end use from current primary users, such as chemicals and petrochemicals, and following, for the decarbonization of certain sectors industries such as steelmaking to use in district and industrial heating. In addition to primary uses, hydrogen is also seen within the European Strategy as an enabler for the

decarbonization of transport, and in integration with the process of transport electrification.
In summary, the goals set out in the European Strategy aim to grow the use of hydrogen in final consumption from the current level of 2 % to 14 %, with a target of installing 40 GW (plus an additional 40 GW in neighbouring geographies to the east) by 2030 and reaching 500 GW of installed electrolyser capacity in 2050.
The total investments will be very large, around 320-458 bn € by 2030, including 220-340 bn € to increase the photovoltaic and wind power generation capacity subservient to the production of clean hydrogen.

2.2.1. Hydrogen classification issue

In May 2021, in line with the Commission, the European Parliament, through its own **resolution** [61], adopted its position on the classification and regulation of hydrogen, which it expresses by clarifying that:

- a legal classification of different types of hydrogen at the Union level is indispensable and must be: comprehensive, precise, science-based and uniform. And constitute a reference for the definitions that will then be given at the national level.
- the classification of different forms of hydrogen should not use a color-coded approach, but should be determined by independent, science-based assessments, and *"believes that such classification should be based on life-cycle greenhouse gas emissions throughout the hydrogen production and transportation process, but should also take into account transparent and robust sustainability criteria, in line with the principles of the circular economy, and be based on averages and standard values per category, such as the goals of sustainable use and protection of resources, waste management and increased use of raw and secondary materials, pollution prevention and control, and, finally, protection and restoration of biodiversity and ecosystems."*
- Notes that there is a discrepancy between the different definitions of clean hydrogen used by different bodies, and further notes that it is necessary to avoid using two names for the same category of hydrogen, namely "renewable" and "clean," proposing to use only "renewable hydrogen"

2.2.2. RePoweEU

The European Commission is advancing the European hydrogen strategy by expanding its expectations for renewable hydrogen as a key energy carrier with the goal of moving Europe off of Russian fossil fuels by 2030 with the publication of a new **Communication**, the RePowerEU plan [29], in May 2022.

The Commission describes a "hydrogen accelerator" idea to promote the deployment of renewable hydrogen, which will aid in accelerating the energy transition and decarbonizing the EU's energy system, in the "Commission staff working" paper.
The RePowerEU plan seeks to generate 10 Mt of renewable hydrogen domestically and import 10 Mt. According to the working paper [40], the 40 GW target of the July 2020 European Hydrogen Strategy, raised to 44 GW of the Fit for 55 package (July 2021) would both be significantly and again increased by this up to 65-80 GW of electrolysis capacity in the EU.
Accelerating the use of hydrogen, ammonia, and other renewable derivatives in hard-to-abate industries including transportation and energy-intensive industrial processes is the aim of these initiatives. Those are important industrial sectors to boost hydrogen adoption in the EU.
At the same time as the RePowerEU was published, the Commission launched two consultations on two delegated acts that would have clarified the EU regulations that would apply to renewable hydrogen under the 2018 Renewable Energy Directive. The first proposal outlines criteria for goods that come under the renewable hydrogen category and covers renewable fuels with an non-biological origin. To reach the GHG emission reduction target established by the Renewable Energy Directive, the second proposal provides a thorough plan for calculating the life cycle emissions of renewable hydrogen and recovered carbon fuels.

2.3. The European Regulatory framework

2.3.1. The RED II (Regulation 2018/2001) and Delegated Acts in draft

In order to carry out an exhaustive examination of this European Legal Act, it is first useful to mention some definitions established by the same Act:

‘**energy from renewable sources’** or ‘**renewable energy’** means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas;[62]

‘**renewable liquid and gaseous transport fuels of non-biological origin’** means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass;

‘**guarantee of origin’** means an electronic document which has the sole function of providing evidence to a final customer that a given share or quantity of energy was produced from renewable sources;

‘**biomass**’ means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin;

‘**biomass fuels’** means gaseous and solid fuels produced from biomass;

‘**biogas**’ means gaseous fuels produced from biomass;

RED II Directive establishes a common framework for the promotion of energy from renewable sources, starting with a set of definitions including those mentioned above and with the additional objectives of:

- Set the overall share of energy from renewable sources in the Union's gross final energy consumption in 2030;
- Dictate standards for the use of energy from renewable sources in the transportation sector;
- Set sustainability and GHG emission reduction criteria for biofuels, bioliquids and biomass fuels.

In this context, **renewable hydrogen** is classified among

- "**Renewable liquid and gaseous transport fuels of non-biological origin**" (RFNBO)
- "**biomass fuels**" that achieve a 70 % reduction in greenhouse gas emissions compared to fossil fuels, setting specific sub-targets for renewable hydrogen consumption (50 % of total hydrogen consumption for energy use and as feedstock in industry by 2030 and 2.6% of energy supplied to the transportation sector).

RED II introduced a sub-target for the use of renewable energy in the transport sector (Art. 25) under which Member States must require fuel suppliers to ensure a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy. This led to Member States requiring the fuel suppliers to blend increasing amounts of biofuels and other renewable energy carriers into the likes of gasoline and diesel. One alternative to biofuels are the RTFNBO, which under current technological conditions translates to hydrogen based fuels. In its Article 27 RED II introduced the main requirements to determine the share of renewable electricity used in the production of such synthetic fuels in order for them to qualify as RTFNBO.

A constraint related to the strategy is the further guidance posed by RED II where, considering the proposal by the European Commission for the production of liquid or gaseous renewable fuels, it is assumed that hydrogen can be considered "clean" only when it should meet the principles of:

1. Additionality, where the renewable electricity produced and used for hydrogen production must be additional to that produced by existing RES plants; the electricity used by the electrolyser must come from facilities that came into service no more than 3 years before the electrolyser
2. Temporal correlation: where renewable electricity must be produced at the same time as hydrogen generation to avoid generating imbalances within the power grid (with a 1-hour verification interval from 2027, subject to the transitional phase during which such verification is done on a monthly basis);
3. Spatial correlation: lack of congestion in the power grid, where hydrogen production must not result in excess electricity fed into the grid or excess capacity connected to the grid.

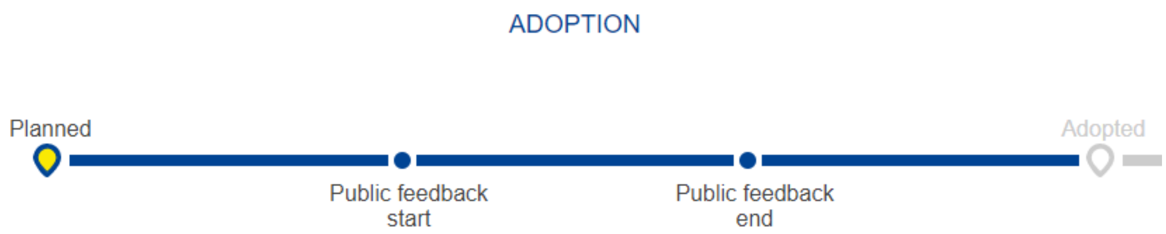


Figure 31 - Extract of Adoption timeline infographics on Proposed Delegated act on the criteria for RTFNBO. Source: https://webgate.ec.europa.eu/regdel/#/delegatedActs/1421

There are actually two draft delegated acts that propose process and production method (PPM) requirements for hydrogen or its derivatives to be included in the binding renewable energy targets of member states set forth in the Renewable Energy Directive (RED II) were published by the European Commission in tandem with the REPowerEU Plan in 2022.

RED II led Member States to search for alternative and effective solutions to achieve such ambitious goals, with renewable liquid and gaseous transport fuels of non-biological origin (RTFNBOs) taking on a pivotal role. Under RED II, RTFNBOs are generally translates to hydrogen-based fuels.
The drafts of the long awaited RED II delegated acts are:

a) the draft RED II Art 27(3) delegated act establishing the criteria for RTFNBOs classification (the Green Hydrogen Rules);
b) the draft RED II Art 25(2) and 28(5) delegated acts setting a minimum threshold for GHG emissions savings of recycled carbon fuels and the methodology by which to assess the GHG emissions savings from RTFNBOs and recycled carbon fuels (the GHG Emissions Rules).

The Draft on Green hydrogen rules provides three options:

1. the share of renewable energy used for RTFNBO production of RTFNBO can be determined by the average share of electricity from renewable sources in the

country of production, measured two years prior to the year of production (the average share option);

2. electricity obtained from a renewable generation plant directly connected to or within the same fuel generation plant will be treated as renewable (and thus the fuel potentially an RTNFBO) provided that the plant generating renewable electricity
   a. comes into operation after, or at the same time as, the facility producing the RTFNBOs; and
   b. is not connected to the grid or is connected to the grid but it can be demonstrated that the electricity in question was supplied without taking electricity from the grid, (the direct line option);
3. even when the electricity is taken from the grid, such electricity may be treated as renewable provided that such electricity is produced exclusively from renewable sources and other appropriate criteria have been demonstrated, ensuring that the renewable properties of such electricity are claimed only once and only in an end-use sector (the supply-to-grid option).

The hydrogen standards build on these three options in the delegated acts, are developed graphically as: additionality; temporal correlation; and spatial correlation in the Table 9.

Table 9 - Solutions for renewable hydrogen [63].

	Direct Line Option	Grid Delivery Option	Average Share Option
Additionality	– New renewable installations or significantly retrofitted required. – Renewables to come into operation no earlier than 3y prior to electrolyser installation (or 2y after installation for additional capacity).	– New renewable installations or significantly retrofitted required. – Additionality not applicable to the initial production capacity of RTFNBOs installations that come into operation before 1 January 2027. – From 1 January 2027: – renewables operation to come into operation no earlier than 3y prior to electrolyser installation (or 3y after installation for additional capacity). – renewable plant must not have received operating aid or investment aid (with some exceptions)	N/A
Spatial correlation	– Physically linked renewable electricity generation. – Production of renewable electricity and RTFNBOs in same installation or in different installations connected through a direct line.	– Grid connected with power purchased under a PPA with an economic operator producing renewable power. – Renewable energy production unit is located: – in the same bidding zone as the electrolyser; or – in a neighbouring bidding zone with aligned or higher prices; or – in an offshore bidding zone adjacent the RTFNBOs installation zone.	N/A
Temporal correlation	N/A	– Until 31 December 2026: – temporal correlation requirement is one calendar month (except for projects that receive state aid support that is not CAPEX based, which remains one hour). – From 1 January 2027: – hydrogen to be produced in the same hour as renewable electricity is generated. – if hydrogen produced from power from behind the meter storage, renewable electricity to have been charged into storage within the same hour as renewable electricity produced. – during a one-hour period where the clearing price of electricity resulting from single day-ahead market coupling in the bidding zone is lower or equal to EUR20 per MWh or lower than 0,36x the price of an ETS emission allowance.	N/A
Other Criteria	N/A	N/A	– Electrolyser to be in bidding zone with more than 90% renewables. – Cap on full-load hours depending on share or renewables.

The Green Hydrogen Rules apply to projects all around the world. They specifically state that the regulations would be followed whether or not the RFTNBO was made in the EU. Any producers or distributors of hydrogen who are interested in the European downstream markets will thus need to be aware of the arrangements outlined in the Green Hydrogen Rules. In any case, the EU is seen by many participants in the developing hydrogen value chain as the gold standard for sustainability criteria regarding green hydrogen.

It is unclear how some Green Hydrogen Rules ideas will be applied to industrial endeavors outside of the EU.

Table 10 - Level of discussion regarding clean hydrogen in the EU and how it compares to the emerging regime in the UK [63].

	UK – Low Carbon Hydrogen Standard	RTFNBO under RED II (and delegated acts)
Purpose	Access to subsidy/support schemes	Contribution to EU renewable energy use targets
Direct connection/ private wire power permitted	Yes	Yes
Grid connected power (via PPA) permitted	Yes	Yes
Grid import power permitted	Yes	Yes
Additionality requirement	No* *but may be part of subsidy eligibility criteria	Yes
Temporal correlation requirement	30 minutes	1 hour
Geographical correlation requirement	No	Yes
GHG emissions requirement	20g CO2e/MJ LHV at point of production	70% GHG emissions savings (in comparison to fossil fuel) at point of use
Transitional arrangements	No	Yes

2.3.2. Taxonomy and its Delegated Regulation (EU) 2021/139

This Delegated Regulation [64] includes to date the most important criteria for defining the sustainability of hydrogen production.

The GHG emissions threshold (under the criteria of substantial contribution to climate change mitigation) for hydrogen production has been set at 73.4%, with **GHG emissions below 3tCO2/tH2** (total carbon dioxide per total hydrogen) **on a life cycle basis**.

Hydrogen fuel production is included among eligible activities. The Delegated Regulation requires that GHG emission reductions be calculated using the methodology of the international standard ISO 14067:2018 or ISO 14064-1:2018 or, alternatively, the methodology to be adopted by the Commission under Article 28(5) of the Renewable Energy Directive ("RED II"), i.e., the methodology for assessing greenhouse gas emission reductions from liquid and gaseous renewable transportation fuels of non-biological origin.

2.4. The Italian Strategy

Table 11 - Major legislative and policy initiatives in Italy in recent years.

YEAR	STRATEGIC INITIATIVE
2016	Decreto Legislativo 16 Dicembre 2016, n.257 (adoption Directive EU 2014/94)
2018	Decreto 23/10/2018 Ministero dell'Interno «Technical standard» Of fire prevention for design, construction and operation of hydrogen distribution systems for automotive use.
2019	Hydrogen is included in the PNIEC
2020	Preliminary guidelines for an Italian strategy on hydrogen
2021	3.64 billion € for hydrogen in the PNRR
2022	notified the IPCEIs on hydrogen.

2.4.1. Strategia Energetica Nazionale (SEN)

The SEN 2017 includes hydrogen in a marginal way, in any case confirming its potential in RES integration, electric storage, and Power-To-Gas.

2.4.2. PNIEC

In the PNIEC, hydrogen production is mentioned for its possible contribution to pursuing security and flexibility goals, thinking about its use and increasing integration of gas and electricity grid infrastructures.
There is a mention of the role of hydrogen for energy storage. Alongside pumping and electrochemical storage, it is intended to promote the development of other technologies that enable energy storage. Among these, a prominent role may be played in the long term by power to gas, which has already been written about, that is, the production of hydrogen and/or synthetic methane from renewables.
Regarding non-biological renewable fuels, the PNIEC assumes for hydrogen a contribution, around 1 % of the RES-Transport target, either through direct use in hydrogen cars, buses, and trains (for some non-electrified routes) or through the introduction of methane into the grid also for transportation use.

2.4.3. PTE

It is required to boost the PNIEC targets in order to meet the ambitious goals set forth by the "Fit for 55" package, which elevates some of the macro goals included in the European Green Deal. A modification is thus anticipated; it is now being written and is due for publication in 2022.

Pending this update, the Ministry of Green Transition has adopted the Piano per la Transizione Ecologica (PTE), which provides an environmental and energy policy framework integrated with the goals already outlined in the Piano Nazionale di Ripresa e Resilienza (PNRR).

2.4.4. The preliminary guidelines of the Italian hydrogen strategy

In line with what the European Commission presented in the hydrogen strategy, pending the official publication of the National Hydrogen Strategy, the Ministry of Economic Development (MiSE), in 2020, issued some guidelines regarding the implementation of the national strategy for a hydrogen supply chain development. The national program envisages a gradual development of the market, using hydrogen from SMR in the short to medium term to bring into being and develop a supply chain to date in an embryonic state, but with the goal, by 2050, to envisage a decisive penetration of clean hydrogen.

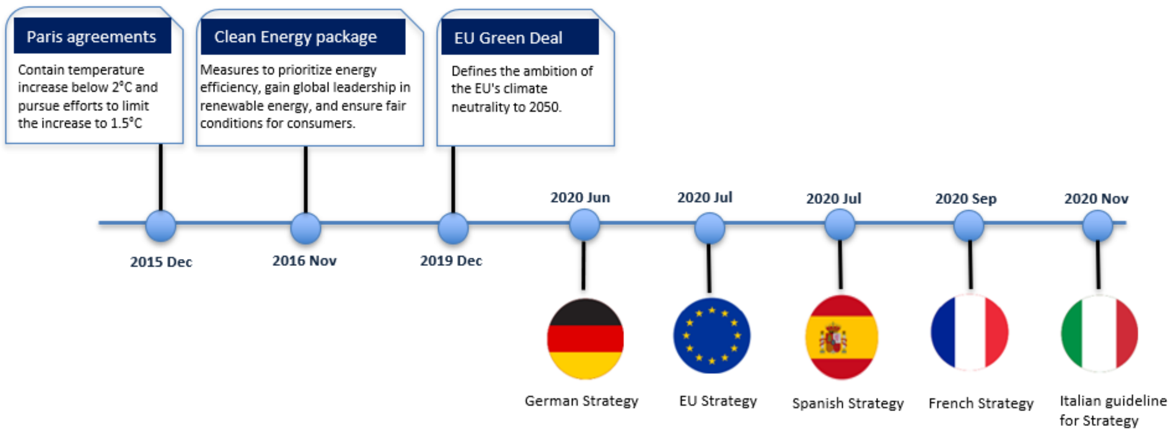


Figure 32 - Initiatives and EU Strategies timeline.

The program, in order to predict a 2% penetration of hydrogen in final energy consumption, identifies certain sectors/end uses; specifically, we find:

- Chemical industry and refineries: in these realities, hydrogen is already used for the production of basic chemicals (ammonia and methanol) and in refining processes
- Hydrogen blending in the existing gas network: the forecast is to replace about 2 percent of natural gas transported with hydrogen

- Mobility: Long-haul trucks (ensuring coverage by 2030 of about 2% of the fleet on the road) and trains (ensuring coverage by 2030 of about 50% of non-electrifiable routes)
- Creation of Hydrogen Valleys: Examples include early applications such as the South Tyrol Hydrogen Valley and the Brescia-Iseo-Valcamonica Hydrogen Valley.
- Other pilot projects: Local Public Transport (LPT), biological methanation and use of hydrogen in the secondary steel industry

In order to envisage hydrogen penetration in final energy consumption of at least 20 % by 2050, within the program, in addition to the development of hydrogen use in the sectors/end uses envisaged in Phase 1, additional fields of hydrogen application are identified: residential heating, industrial heating, Mobility, hard-to-abate sectors, and flexibility services with respect to grid needs.

Within the preliminary guidelines of the Ministry of Economic Development, forecasts are given for achieving important results as early as 2030:

- about 2% as a forecast for hydrogen penetration in final energy demand
- 5 GW of electrolysis capacity for hydrogen production
- 8 Mt CO_2 less, equivalent to a 4% reduction on PNIEC targets
- 200,000 new jobs

At the level of Economics:

- 27 billion € of expected incremental impact on GDP
- 10 billion € in investment over the 2020-2030 decade
- 5-7 billion € in H2 production technologies
- 2-3 billion € in distribution and consumption facilities (trains, trucks, filling stations)
- 1 billion € in R&D and infrastructure to integrate supply and demand

2.4.5. PNRR

In addition to the measures envisaged within the guidelines published by the MiSE at the end of 2020, the final text of the PNRR was released in April 2021, which dedicated approximately 3.7 billion € to hydrogen-related projects, out of the more than 25 billion € allocated for the M2 component C2 mission. In particular, we highlight the presence of 2 reforms and 6 investment lines for the development of this market.

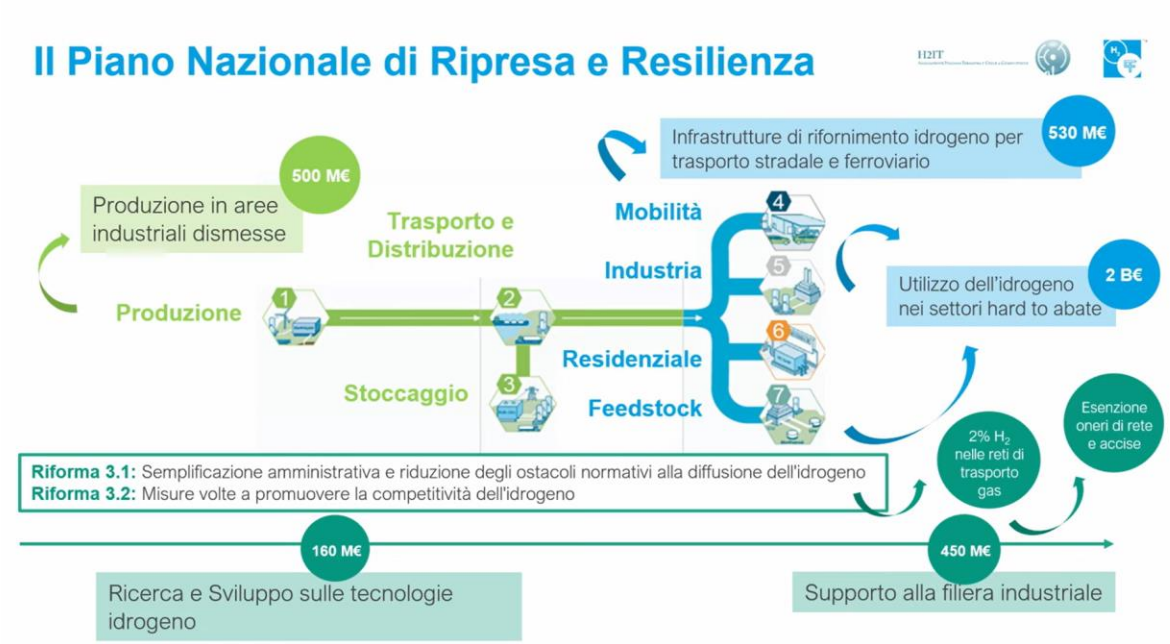


Figure 33 - Allocation of economic resources of the PNRR [65]

2.4.6. Hydrogen IPCEI

[66]European Commission Decision C(2022) 5158 final of July 15, 2022 authorized state aid from fifteen countries (Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Italy, the Netherlands, Poland, Portugal, Slovakia, and Spain) to support the implementation of the first major project of common European interest (IPCEI) on technologies for the creation of a European hydrogen value chain, called "IPCEI Hy2Tech" (also IPCEI H_2 Technology or IPCEI Hydrogen 1). The IPCEI H_2 Technology (IPCEI Hydrogen 1) supports research, development and innovation activities, including included in the first industrial application, along a large part of the hydrogen value chain.
The objective of the Project is to contribute to the Decarbonization of the economy by fostering the replacement of fossil fuels with hydrogen through the development of a whole set of innovations in production technology, including in chemical and realization processes, and further innovations in the entire value chain, which would be unfeasible without the use of the Important Project of Common European Interest instrument.
Aid authorized at the EU level amounts to 5.4 billion € in total. For the support of the implementation of IPCEI Hydrogen 1, in first implementation, resources amounting to 700 million € are activated in total, of which:

- 450 million € from the resources of PNRR intervention M4C2-I2.1 - Mission 4 "Education, Training, Research," Component 2 "From Research to Enterprise," Investment 2.1 "Major Projects of Common European Interest (IPCEI)."

- 250 million € from the resources of NRP intervention M2C2-I5.2 - Mission 2 "Green revolution and ecological transition," Component 2 "Renewable energy, hydrogen, grid and sustainable mobility," Investment 5.2 "Hydrogen."

2.4.7. National Long-Term Strategy

The proposed National Long-Term Strategy (LTS) identifies possible pathways to achieve a "climate neutral" condition in our country by 2050.
After outlining a Baseline Scenario characterized by hitting the targets set by the PNIEC, combinations, synergies and criticalities of potential levers that can be activated are identified including a radical change in the energy mix in favor of renewables (RES), combined with deep end-use electrification and hydrogen production.

2.5. The Italian Regulatory framework

2.5.1. The Decreto Legislativo n. 199/2001 – RED II enacted

Italy with Decreto Legislativo (DLgs) 199 of 2021 [67] enacted and implements the RED II directive.

In addition to what is already defined and regulated by RED II, DLgs 199/2021, in Art. 39, introduces with reference to the use of energy from renewable sources in the transport sector:

- The mandatory for fuel suppliers to achieve by 2030 a share of at least 16 % of renewable sources in the total fuel released for consumption in the reference year and calculated on the basis of energy content;
- The possibility of achieving the target mentioned in the previous point (see Art. 39, para. 1) through biofuels and biomethane or biogas for transport (Art. 39, para. 5).

2.5.2. Decreto del Ministero della Transizione Ecologica – 21/09/2022

Concerns the conditions for access to subsidies on the consumption of renewable energy in electrolysis plants for the production of green hydrogen

In light of Decreto Legge n. 36 of April 30, 2022, converted, with amendments, by Legge n. 79 of June 29, 2022, on "Further Urgent Measures for the Implementation of the National Recovery and Resilience Plan (PNRR)," and, in particular, with reference to Article 23, which introduces tax incentives to support green hydrogen production and consumption in the transportation sector, the Ministry of Transition identifies the cases and conditions for access to the facilities.

Specifically, in Article 3, "Technical Conditions for Access to Facilities," of the **Decreto del Ministero della Transizione Ecologica - September 21, 2022** considers hydrogen produced by electrolytic process from renewable energy sources (i.e. backed by guarantees of renewable origin), i.e., hydrogen that meets the life cycle greenhouse gas emission reduction requirement of 73.4 percent compared to a reference fossil fuel of 94 g CO2e/MJ i.e., **hydrogen that results in less than 3 tCO2eq/tH2.**

This type of hydrogen takes the definition of "**green hydrogen**".

2.5.3. Decreto 30 giugno 2022 n.198 - MiMS

It establishes the requirements for funding the hydrogen experiment for rail transport included in the "M2C2.4 Developing more sustainable local transport" component of the PNRR) [68]. Specifically, the intervention provides for the conversion to hydrogen of non-electrified railway lines in "regions characterized by high traffic in terms of passengers with a heavy use of diesel trains such as Lombardia, Puglia, Sicilia, Abruzzo, Calabria, Umbria and Basilicata" and for "the most advanced feasibility projects in Valcamonica and Salento" "the experimentation in an integrated way of production, distribution and purchase of hydrogen trains." The total resources available amount to 300 million euros. The allocation of resources is regulated by a subsequent Ministero delle Infrastrutture e della Mobilità Sostenibile (MiMS) Decreto Ministeriale.

The Decree, in relation to hydrogen production, establishes some specific requirements (art.1, paragraph 4) that ensure its effective environmental, as well as economic, sustainability.

More specifically, it is established that:

- in compliance with EU Regulation 2021/241, investment programs shall not cause significant harm to environmental objectives in accordance with Article 17 of EU Regulation 2020/852;
- the investment programs must comply with the principle of additionality and in any case with the requirements contained in the approving Delegated Act, once it enters into force ("EU Delegated Act"), of Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, which defines the rules for the production of transport fuels, liquid and gaseous, that are not of biological origin.

It is, moreover, provided that the selection of project proposals will be made according to the following criteria (Art. 3, paragraph 4):

- the level of sustainability of the proposed project, with specific regard to, among others, environmental, economic-management aspects and the timetable for implementation of the intervention;
- the proximity of the hydrogen production centers to the railway line that is the subject of the project proposal, regardless of the location of the production of electricity from renewable sources (RES) used for the production of hydrogen, consistent with the provisions of Article 23 of DL 36/2022, converted into Law 79/2022, subject to compliance with the principle of additionality and in any case the requirements of the approving EU delegated act;
- the level of consistency with the investments of the M2C2 component of the NRP;
- the level of maturity of the project proposal and its economic-financial sustainability.

2.5.4. Technical standards -Hydrogen refueling station

Regarding infrastructure, the Ministry of Infrastructure and Sustainable Mobility specifies that the implementation of hydrogen experiments in the rail and road transport sectors implies the need to pay attention to the preparation of technical standards for rail and road transport safety.

The ministerial standard (Decreto 199 del 30-06-2022), in compliance with the provisions of the PNRR on hydrogen experimentation for road transport:

- defines a total investment of 230 million € for the development of a hydrogen experiment for road transport through the establishment of at least 40 hydrogen refueling stations for light and heavy vehicles [69];
- Identifies technical criteria for construction;
- Indicates a priority for the location of refueling stations.

The Ministry's own notice of 10/11/2022 initiates the selection of project proposals for the construction of renewable hydrogen-based refueling stations for road transport, to be funded under the NRP and then financed through NGEU[70].

CASE STUDY

Non-recyclable waste is collected and conveyed to a Waste-to-Energy (WtE) plant, which generates electricity through its combustion. Currently, the electricity produced is sold to the electricity grid. This case study takes into account the possibility of using part of this energy to produce hydrogen through an electrolyser and using this new resource to power the mobility of an adjacent area.

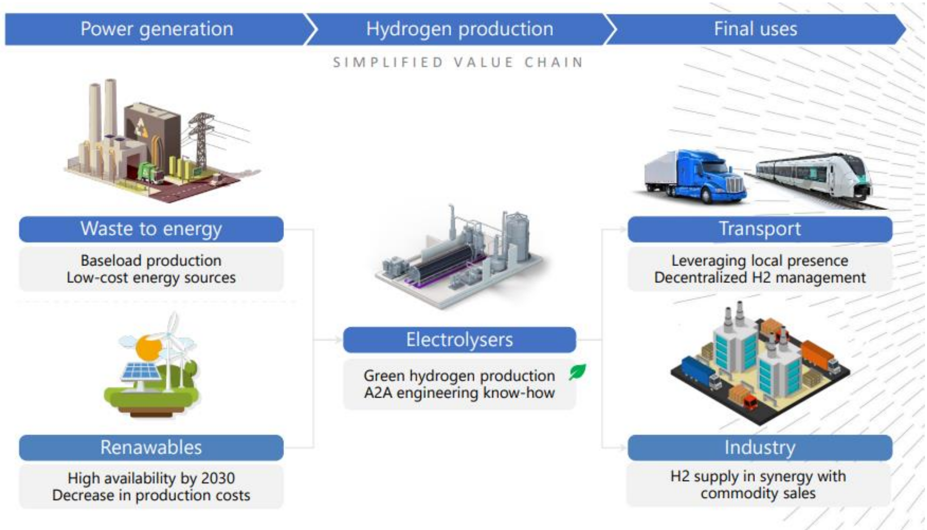


Figure 34 - Value chain -production: green hydrogen will be a key factor for decarbonization of uses: Source: "Mobility: Infrastructure and services" course – Polimi.

As represented in Figure 34, the green hydrogen produced by an electrolyser using electricity produced by the WtE and from renewable sources can then be used to provide the energy needed for the mobility sector or more generally in the hard-to-abate sectors.

This case study will be developed in two parts:

- The first will describe how the technology used in WtE plants makes it possible to obtain the electricity to power an electrolyser, and in particular through what type of waste, what class of hydrogen it is, and the certifications that allow the origin of the product to be transparently traced. Reference is made to the LCA methodology for calculating the Carbon Footprint, and finally to the opportunities offered by the use of the WTE plant itself and its costs, compared to the use of other RES.
- The second part describes the H2IseO Hydrogen Valley project feed also by the hydrogen products by Brescia WtE in H2Valcamonica project, and the declared and potential uses that can be made of it in the mobility sector, in compliance with current legislation.

3 Hydrogen production from an electrolyser fed by the Brescia Waste-to-Energy plant (WTE)

3.1. Waste management

A comprehensive legislation has been built in the EU with objectives and targets to improve waste management, as well as to reduce GHG emissions and adverse health and environmental impacts. Waste management has been developed in the EU on the concept of a hierarchy of options, which includes a legally binding prioritisation of waste management activities. The waste hierarchy is essential to the shift to a circular economy. For these reasons, the order of priority follows the hierarchy shown in Figure 35.

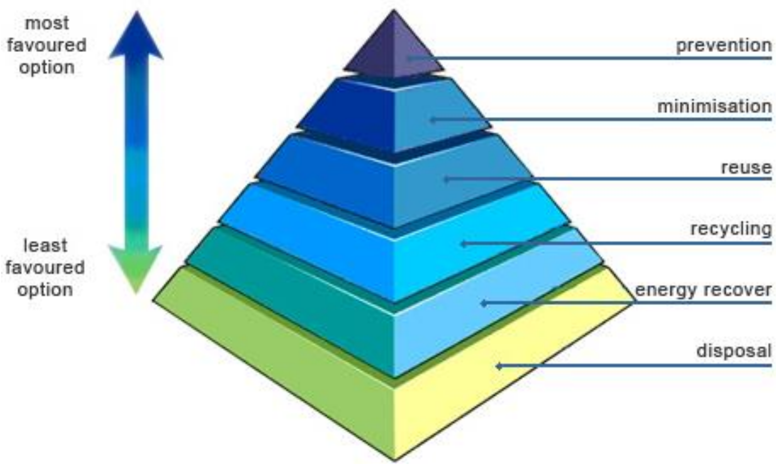


Figure 35 - Waste management hierarchy in accordance with Article 4 of Directive 2008/98/EC [71]

In essence, waste prevention is the most desirable option, followed by material recovery and recycling (metal, glass, paper recycling or organic waste composting), energy recovery from waste (through incineration, or digestion of biodegradable wastes) and finally disposal (landfilling) with no recovery of either materials and/or energy as the least desirable option.
Waste management encourage material reuse in light of the circular economy, decrease landfilling, and ultimately generate energy.

According to the goals of Circular Economy Package [72], real recycling will be 65% and landfilling will be 10%. The remaining 25% of garbage must be valued through energy recovery in order to complete the waste management.

Waste-to-energy (WtE) conversion processes, as a source of renewable energy, are expected to play an increasingly important role in sustainable management of municipal waste at global level. It is estimated that a reduction of about 10–15% in the global GHG emissions could be achieved through improved solid waste management (recycling, waste diversion from landfill and energy recovery from waste).

Figure 3 shows the percentage breakdown of municipal waste management in the EU27, year 2019 [73] . It is evident that the non-recycled part follows different processes; one of these is energy recovery (R1) through the use of Waste-to-Energy plant.

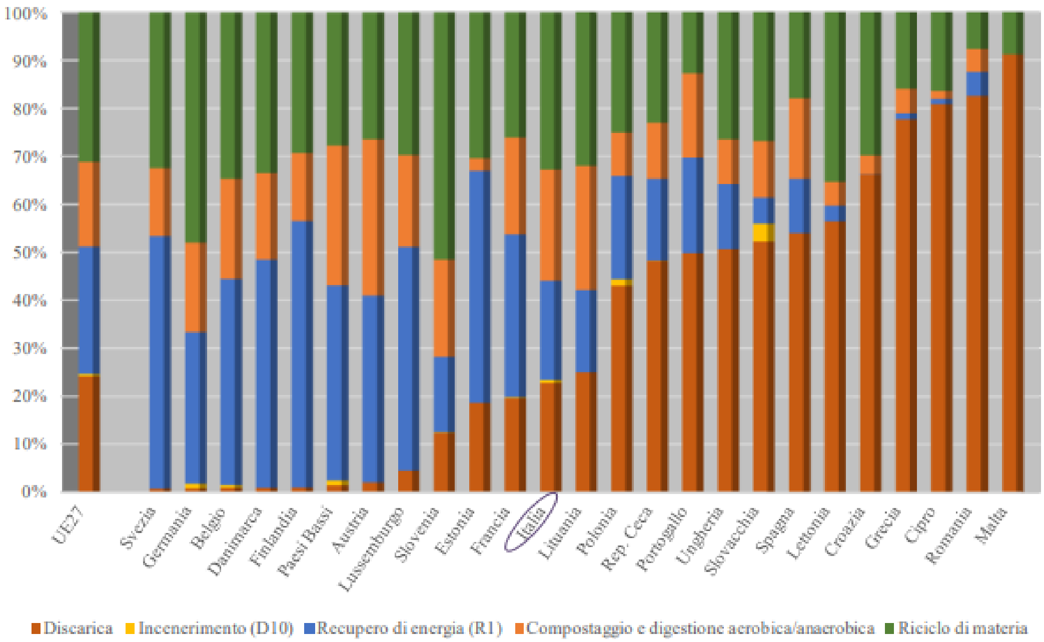


Figure 36 - the percentage breakdown of municipal waste management in the EU27, year 2019. Source: ISPRA 2019

There is extreme variability in the approach to municipal waste management between different Member States. Sweden, Germany, Belgium, Denmark, Finland, the Netherlands, Austria and Luxembourg prefer incineration with energy recovery (R1) with respect to landfilling (below 4.5%), with percentages ranging from 32% in Germany to 56% in Finland. Incineration without energy recovery (D10) is little used and the highest percentage is found in Slovakia (4%). Countries with percentages of municipal waste sent to composting and digestion exceeding 20% of the total treated are: Austria (33%), the Netherlands (29%), Lithuania (25%), Italy (23%), and Belgium (21%).

Energy recovery of waste can also contribute substantially to reducing landfilling. Energy recovery plants in Italy produced 4.5 TWh of electricity (1.6 % of total electricity production in Italy) and 2.3 TWh of thermal energy in 2020. The amount of electricity produced by waste-to-energy saw a gradual increase between 2011 and 2020, while thermal production almost doubled its value, rising from 1.3 TWh in 2011 to 2.3 TWh in 2020 (+77%).
This practice, however, is not yet sufficiently widespread in the Italian regions. As can be seen in Figure 37, Italy still has ample room for improvement in the energy recovery of waste compared to the *best performing countries*.

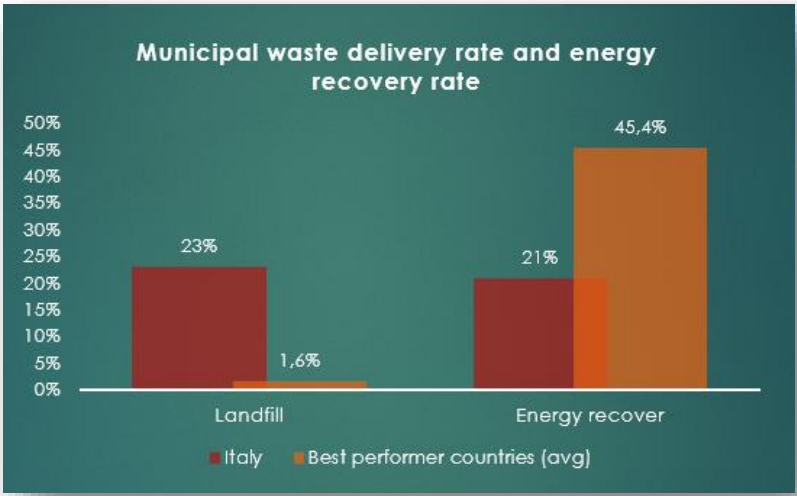


Figure 37 - Municipal waste to landfill rate and energy recovery rate in Italy and *Best Performer Countries* (Switzerland, Sweden, Germany, Belgium, Denmark, Finland, Netherlands, Austria, Norway, Luxembourg - average % values), 2020 Source: elaboration on ISPRA data

To date, 6 out of 20 regions are not equipped with energy recovery plants. Among the most virtuous regions there is Lombardy, which has 13 municipal waste-to-energy plants by 2020, i.e. more than 35% of those on national soil. The number of plants in the regions is closely linked to the quantity of waste treated. Lombardy ranks first nationally with 1.93 Mt treated in energy recovery plants [32].

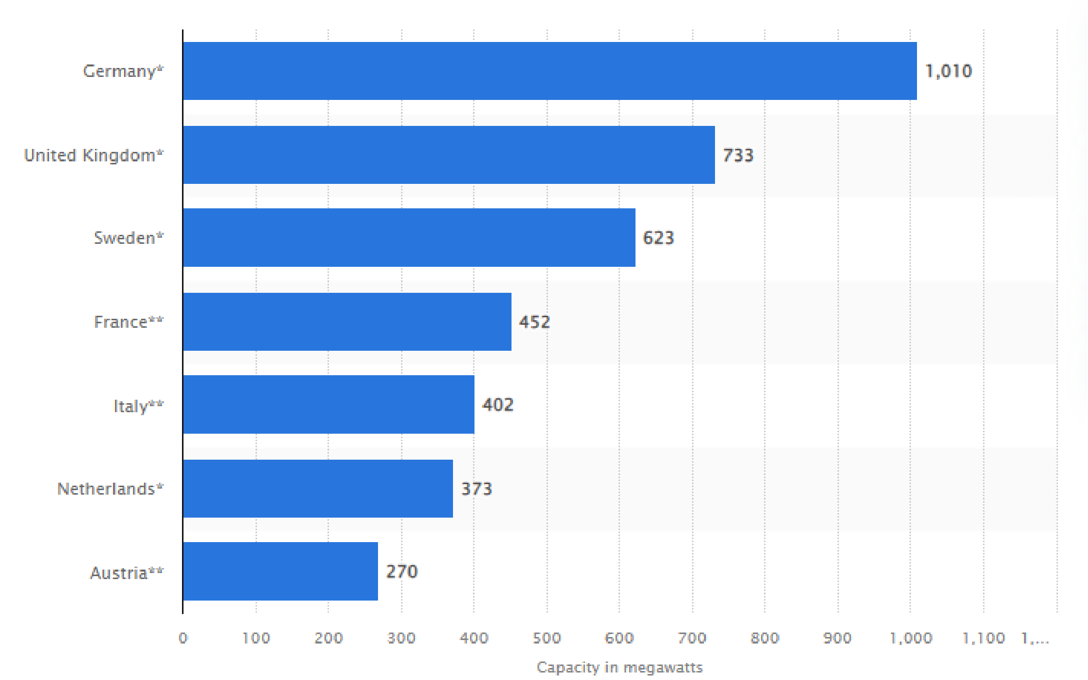


Figure 38- Installed capacity in MW of municipal waste Energy in Europe from 2010 to 2021 by country. Source: https://www.statista.com/statistics/1122082/europe-waste-to-energy-capacity-by-country/

3.2. What is WTE and general data

One of the most popular procedures for managing municipal solid waste is incineration, a thermal treatment method that lead to decrease waste volume by up to 90%. In order to recuperate the thermal energy produced, incineration plants typically include a thermodynamic cycle for power production. They also incorporate several process controls and exhaust gas cleaning procedures to guarantee that the gas emissions adhere to the requirements set by regulatory bodies for the protection of human health and the environment. Fig. 6 shows a schematic diagram of the Energy from Waste process.

Energy recovery from waste has started long time ago with the first waste incinerator built in 1885 in the United States. In 2016, the number of WtE facilities for municipal waste reached 1618 plants worldwide, including 512 plants in Europe, 822 plants in Japan, 88 in the United States and 166 in China. [74]

Table 12 shows the data referring to the year 2015 in terms of capacity and number of waste-to-energy plants in Europe.

Table 12 - Capacity and number of existing WtE plants in Europe in 2015.

	CHP		Electricity only		Heat only		No info		Total	
	Capacity	No	Capacity	No	Capacity	No	Capacity	No	Capacity	No
Andorra			60	1		0		0	60	1
Belgium	1092	7	1099	8	568	2			2759	17
Czech Republic	646	3		0					646	3
Denmark	2899	22		0	975	12			3873	34
Estonia	220	1		0		0			220	1
Finland	528	3		0	595	3			1123	6
France	7048	37	6691	54	1823	28	22	2	15,584	121
Germany	19,312	78	3401	13	1970	7			24,683	98
Hungary	420	1		0		0			420	1
Ireland			300	2		0			300	2
Italy	2356	10	4223	38	114	2	45	2	6738	52
Lithuania	250	1							250	1
Luxemburg			150	1					150	1
Malta			13	1					13	1
Netherlands	5463	7	1342	3	519	2			7324	12
Austria	1171	5	152	1	1711	6			3033	12
Poland	562	4							562	4
Portugal			1238	3					1238	3
Slovakia	215	2							215	2
Spain			1352	8	1210	2			2562	10
Sweden	4905	26		0	1178	13			6083	39
UK	3498	14	5726	26	352	1			9576	41
Norway	885	8	0	0	726	9	57	2	1668	19
Switzerland	3026	22	232	2	625	7	0	0	3883	31
EU	50,584	221	25,687	158	11,016	78	68	4	87,354	461
EEA	54,494	251	25,919	160	12,367	94	124	6	92,904	511
Europe	54,494	251	25,979	161	12,367	94	124	6	92,964	512

Capacity in thousands tonnes

3.3. WtE renewable energy from Biomass

Biomass availability in Figure 39 can be burned to create heat and converted into electricity, in a Waste-to-Energy plant. The most familiar biomass feedstocks for thermal conversion are raw materials such as municipal waste and scraps from paper or lumber mills.

An essential component of the carbon cycle on Earth is biomass. The exchange of carbon between the Earth's atmosphere, hydrosphere, biosphere, and lithosphere takes place through the carbon cycle.

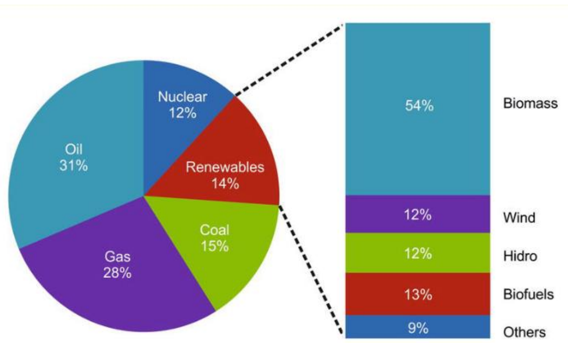


Figure 39 - EU energy mix 2020. Source : Eurostat.

Biomass, as reported in the EU Directive 2001/2018 RED II, is considered a clean, renewable form of energy and electricity generation.

3.4. Brescia plant

Figure 40 - Brescia Waste to Energy plant.

The Brescia Waste-to-Energy plant, in fig. 7, is located in the south of Brescia, in an area of 1,74 km^2, near other a2a production plants connected to the city's district heating network. The WtE Plant makes a significant contribution to the energy needs of the city of Brescia. In fact, in addition to electricity production, it recovers the heat generated and conveys it, through a district heating network of more than 670 km pipes, to the 60000 users' apartments. It produces more than 70% of the energy distributed by the district heating network each year.
In 2006 the Brescia Waste to Energy plant was judged the best waste to energy plant in the world by WTERT (Waste to Energy Research and Technology Council), an organism of the Earth Center of Columbia University in New York.
Active since 1998, Brescia WtE also produces electricity equal to the needs of 200,000 households.

The WTE recovers electricity and heat each year from around 750,000 tonnes of waste that cannot otherwise be recycled. [75]
The plant consists of three combustion lines that burn municipal waste, non-hazardous special waste, and biomass: the first two started working in 1998, the third in 2004.

In 2020, the Brescia Thermal Utility produced and fed into the grid 553 GWh of electricity and 872 GWh of thermal energy.[76]

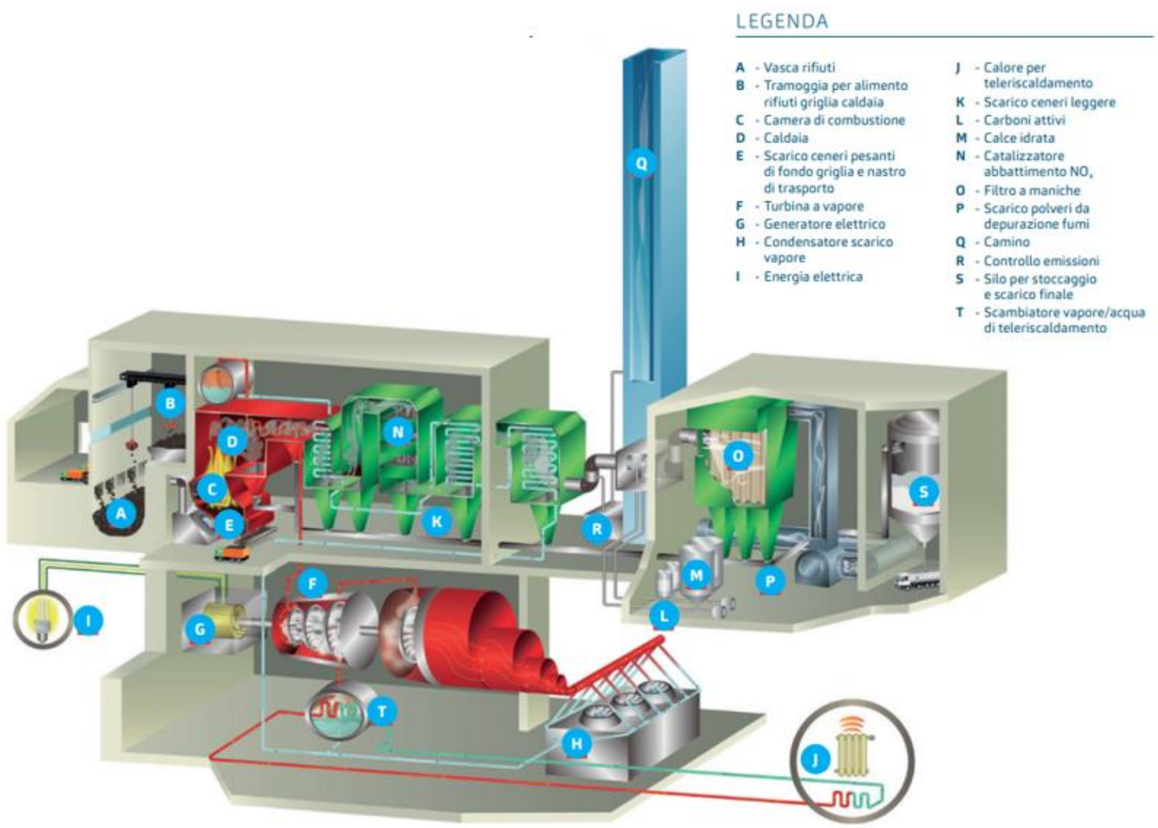


Figure 41 - Operating scheme of the Brescia WTE

How it works

Municipal Waste (i.e., everything not recovered by separate collection within the Integrated Waste System active in Brescia) and non-hazardous Special Waste from commercial and production activities are delivered to the WtE.

Municipal waste is transported to the WTE and, after a thorough initial check, discharged into the collection and mixing tank. From there, via overhead cranes, they are loaded into hoppers that feed the grates on which combustion takes place. The combustion lines consist of steam generators, with combustion chambers whose temperature is constantly regulated to over 1,000 °C, for the complete oxidation of the waste. Heat produced by combustion generates high-pressure steam, which is fed into a turbine for the production electricity and, subsequently, used to heat the water that feeds the city's district heating network. [77]

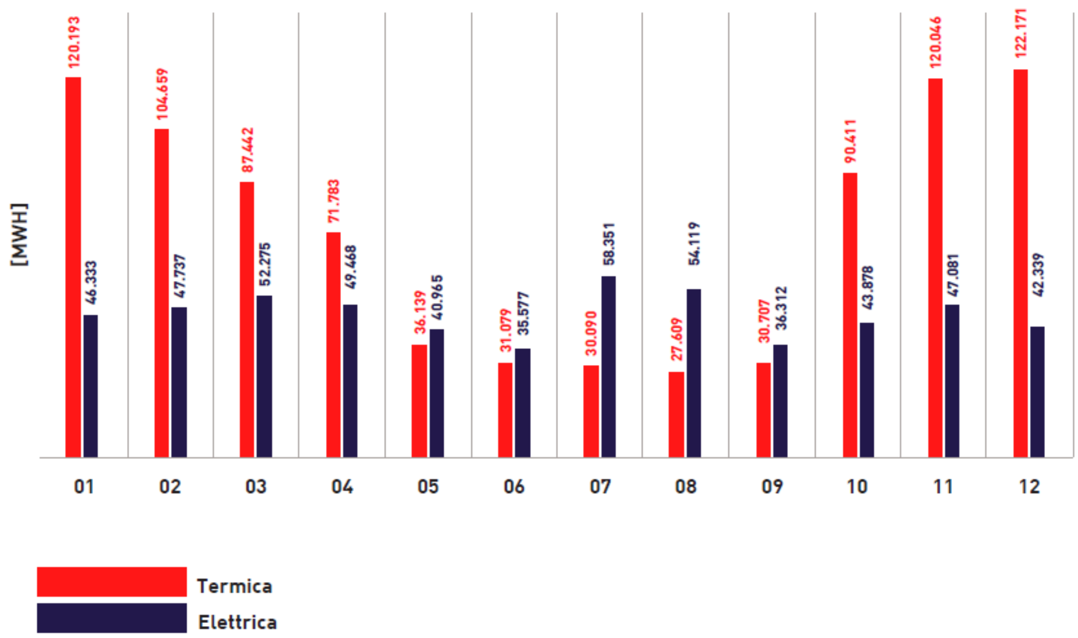


Figure 42 -Net energy production, by month, in the year 2020. Source "Osservatorio Termoutilizzatore - Comune di Brescia" [78]

The cogeneration production system (electric and thermal energy for district heating) enables the plant to achieve a high level of efficiency.
The municipal waste delivered to the plant comes from the of the Lombardy Region, while special waste may originate not only from the Lombardy Region basin but also from outside the region.

3.5. Brescia WtE renewable energy

Brescia WtE is part of the establishment of the Hydrogen Valley H2IseO characterized by the implementation of Sustainable Mobility that will also be powered by hydrogen production through the use of WtE. A portion of Brescia's Electricity production from WtE is renewable; this is the share of power attributable to biomass combustion, exactly 44% which is equivalent to 40 MWe [79]. The certification to be recognized as a renewable source was issued under Article 31, paragraph 1, of the July 6, 2012 Decree of the MISE, by the GSE the Guarantee of Origin of plants powered by Renewable Energy Sources (IGO) [80] , thus allowing the issuance of Guarantees of Origin (GO) on the share of renewable electricity input.
The choice is to use the aforementioned **baseload renewable energy** to power the hydrogen production plant, which can be done through an electrolysis plant.
The electrolyser will be placed in the vicinity of the WTE and directly connected to it just as if it were a kind of self-consumption. The size of the electrolysis plant will be 6

MW with a possible scale up to 21 MW. Potentially, significant amounts of hydrogen can be produced increasing from the current 750 tons per year to 2500-3000 in the case of the scale up. [65]

3.6. Hydrogen originated from biomass: the "Biohydrogen"

According with the RED II Directive (EU Directive 2018/2001), hydrogen originating from the processing of biomass and the use of a Waste-to-Energy plant, through water electrolysis technology, takes on the characteristics of biogas and thus a renewable energy source. [58]

Similarly, following the definitional scheme proposed by Legislative Decree 199/2021, it is therefore possible to define this hydrogen, which we will call "Biohydrogen," a water Biogas that can be used as a gaseous fuel produced from biomass. It is derived from a biological source, and more specifically from the biodegradable fraction of municipal and industrial waste, which, when combusted, takes on the characteristics of a gaseous product.

3.7. Taxonomy and environmental sustainability of "Biohydrogen"

According to the threshold value specified in Section 3.10 of the European Commission's Delegated Regulation (EU) 2021/2139, the hydrogen production have to respect the **threshold value of 3 kg CO_2eq per kg of hydrogen** produced and to be in line with the approach established in Article 25 (2) and Annex V of Directive (EU) 2018/2001.

3.8. Computation of the carbon footprint of "Biohydrogen" through LCA methodology

The reference methodology, specified in Delegated Regulation (EU) 2021/2139 and used by A2A to calculate the Carbon Footprint (ISO 14067:2018) is Life Cycle Assessment (LCA) according to ISO 14040/14044.
By using specialized professional software, the environmental effect evaluation of hydrogen generation was modelled. [79]

The only effect category taken into account in this Carbon Footprint is climate change, in terms of the greenhouse gas emissions from fossil sources, biogenic sources, and land use.
The impact is specifically measured in kg of CO_2 equivalent released. The emissions of each greenhouse gas are multiplied by their equivalence factor (EF), keeping in mind that for carbon dioxide the equivalence factor is 1 by definition. This yields kilograms of CO_2 equivalent.
The LCA model considers the following data:

- the Waste-to-Energy plant data (excluding environmental impacts, which are not taken into account because the facility is already in operation) are literature representative of an average European technology, suitably modified with respect to specific consumption and emissions of the Brescia waste-to-energy plant;
- the electrolyser data refer to an alkaline plant with a size of 6 MW and a useful lifetime of 20 years. There is a direct link between the Waste-to-Energy plant and the electrolyser, which uses demineralized water and 100% renewable power. The electrolyser was designed with the idea that there would be no direct emissions, but that upstream processes throughout the building of its components.
- Among the main plant data considered are a renewable electricity input of 137992.05 kWh/day and 23.965 m^3/day of demineralized water for and an output of 2376 kgH_2/day.
- The functional unit is the kg of hydrogen.

From the results obtained, the impacts in terms of kg CO_2eq emission of the product under study are **1.60 kg CO_2eq/kg H_2**, lower the threshold value defined by the Regulation act of the Taxonomy.

The fossil component accounts for about 99% of the overall impact of the climate change category. The research also reveals that, with a total contribution of more than 85%, the plant's operating phase is primarily responsible for the highest consequences. The supply and consumption of energy produced by burning renewable biomass during the operating phase are the main hotspots in the process, according to the findings.

3.9. Exploiting baseload energy to power an electrolyser

The regulatory framework of biohydrogen has been clarified, and it now appears that it may be result in considerable as "renewable hydrogen," which is promising for its application.

Nevertheless, it is useful to address, including through this case study, the applicability of biohydrogen also with respect to the hypothetical use of other RES.

In this regard, the KPI that is taken as a reference is precisely the cost of this green hydrogen, defined by the LCOH - Levelized Cost of Hydrogen (LCOH) €/kg.

The following Assumptions

Data

LCOH is calculated on the "at the mouth of electrolyser" basis, i.e., immediately downstream of its production (considering the Balance of Plant engineering - BoP). The calculation formula is described by the proposed equation, which provides the most important assumptions used to calculate the levelized cost of hydrogen.

Sources

The literature [79]were used for electrolyser data covering the construction phase of the electrolyser (electrolytic cell and framework) including balance of plant - BOP (inverters, heat exchangers, pumps, tanks), considers an alkaline electrolyser size of 6 MW, 20 years plant life, and other factors.

LCOH methodology

$$LCOH = \frac{I_0 + \sum_{t=1}^{n} \frac{I_t + E_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

I_0	Investment expenditure in year 0
I_t	Investment expenditure in year t (stack replacement costs)
E_t	Electricity consumed in year t including generation costs (wholesale price or RES LCOE + capacity factor), grid costs and taxes when applicable, and electrolyser stack degradation.
M_t	Other operational expenditures in year t
r	Discount rate
n	Life of the system

Figure 43 shows that the cost of hydrogen production related to the load factor of the electrolyser. If the electrolyser use the electricity provided by a Photovoltaic plant (1000 h of production) or a Eolic plant (4000 h of production) is consistently higher than the case in which energy is provided by baseload of WtE. This has the advantage of using the production for 7800 h.

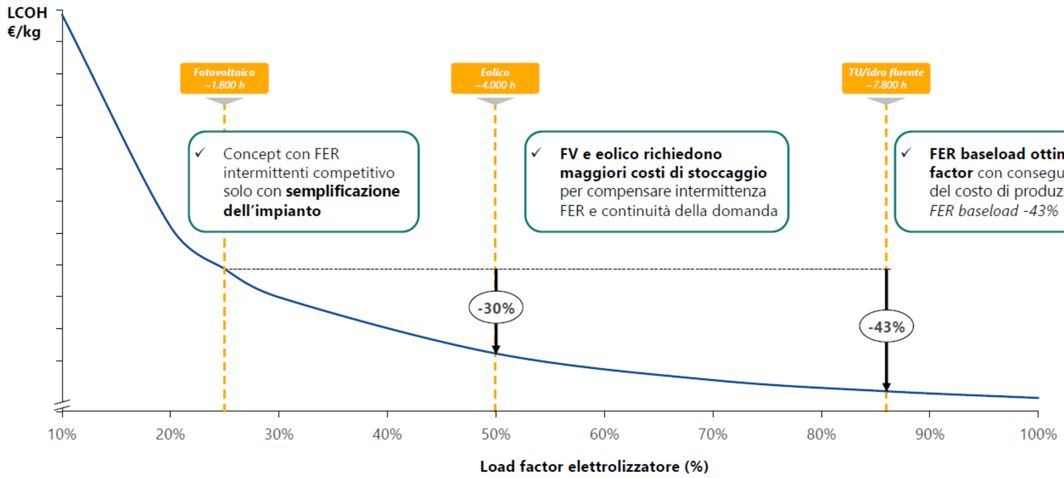


Figure 43 - Load factor of the electrolyser and plant operation. (LCOH is calculated "at the mouth of electrolyze"-considered costs by BoP-engineering). Source: a2a datasheet

Unlike intermittent renewable energy sources, those with production baseloads, such as energy produced through WtE, provide greater competitiveness of the hydrogen produced, in terms of Levelized Cost of Hydrogen expressed in €/kg.

Clearly, this competitiveness must find expression in the scalability of the hydrogen product. With the H2Iseo project outlined in the next chapter, a first user (Trenord) implements a project in which hydrogen is used for the decarbonization of mobility sector: a fleet of rolling stock equipped with a fuel cell technology is used to provide the railway service on the Brescia-Iseo-Edolo line.

4 Hydrogen in Valcamonica Mobility

In this part of the case study we will go into the details of how the Project H2IseO implemented, that involves several players including: a2a as a multi-utility of services/energy with the Project related to biohydrogen from WtE, the FNM Group that manages the railway infrastructure and, through its investee company Trenord, will become the first hydrogen user in Mobility (railway) sector, feeding Fuel cell rolling stock in Valcamonica. The early stages of the Project will be highlighted and hints will be given of the other possible users of hydrogen that will be able to sustain the demand and create the supply chain. In other words, the hypothetical evolution of the value chain that hydrogen is able to create in Valcamonica will be described.

4.1. Hydrogen Valleys

A key role in the development of the hydrogen market within local decarbonization strategies will be played by identifying the presence of potential hydrogen valleys.
A geographic location, such as a city, region, island, or industry cluster, is called "Hydrogen Valley" when several hydrogen applications are brought together to form an integrated hydrogen ecosystem that uses a sizable quantity of hydrogen, enhancing the project's economics. The ideal hydrogen value chain would include production, storage, delivery, and final usage. Therefore, "hydrogen valleys" provide a method to scale up and make the hydrogen technology an effective remedy in decarbonization.
Due to hydrogen's capacity for sectoral integration, "hydrogen valleys" are also crucial for demonstrating the value that hydrogen offers in the larger framework of the energy system. The promise of hydrogen as an integrated systemic solution has not yet been sufficiently proved at scale, despite several demonstration projects having successfully shown maturity and advantages of specific hydrogen technologies, often in pilot or at a small scale.
However, reproducibility is not straightforward when dealing with "Hydrogen Valley" because there is no "unique" solution. Different countries have unique circumstances, particularly in terms of the economic, geopolitical, and environmental situations they are in, as well as the available infrastructure. The transition to a hydrogen economy therefore necessitates different responses depending on the location.

Specifically, hydrogen valleys are characterized by four key elements:

- broad scale, through investment in projects that go beyond the scale of a pilot or demonstration project (identifying potential priority use areas clearly and assessing their impacts and needs);

- geographical boundary defined, with territorial specifications both in terms of geography and in terms of actors involved;
- widespread coverage of the supply chain, from production to hydrogen storage, transportation to end use;
- multi-sector hydrogen supply, versatile use of the resource, and possibility of using it in multiple sectors or applications.

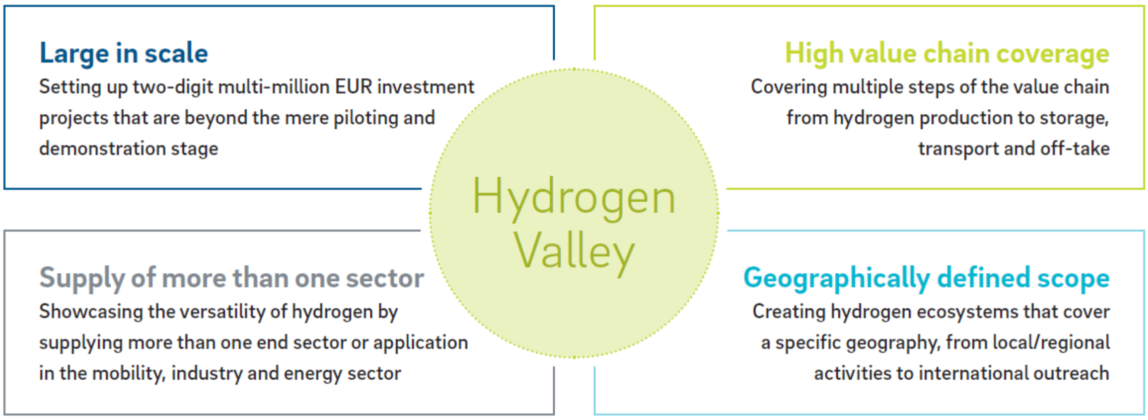


Figure 44 - FCH 2 JU, Inycom, Roland Berger [80]

In the second phase of the European strategy [7], it is planned to install 40 GW of hydrogen production capacity from renewable energy sources, with up to 10 million tons of hydrogen production from renewable sources. To achieve this goal, the European Commission has identified additional initiatives to be pursued jointly, including the development of "Hydrogen Valleys", with definition of an ad hoc infrastructure to provide heat to residential and commercial buildings.

This solution could enable the development of a hydrogen market in the short term; in fact, it would define centralized hydrogen generation and its distribution over short distances to multiple off-takers, leading to a reduction in economic impact by economy of scale.

4.2. H2Valcamonica project

"**Green hydrogen for the decarbonisation of Valcamonica**" is the name of the project in which the coordinating role is played by A2A S.p.a. and the beneficiaries are SNAM S.p.a. and F.N.M. S.p.a.

It has been co-funded by the European Union through the Innovation Fund program.

The ambitious goal of developing Italy's first hydrogen green valley will be greatly aided by this project. The key factor to develop the creation of the first regionally integrated supply chain is an innovative way for all the step of production, storage, distribution, and commercialization of green hydrogen for both transport, Mobility and logistic sectors and Energy Intensive Industries.[81]

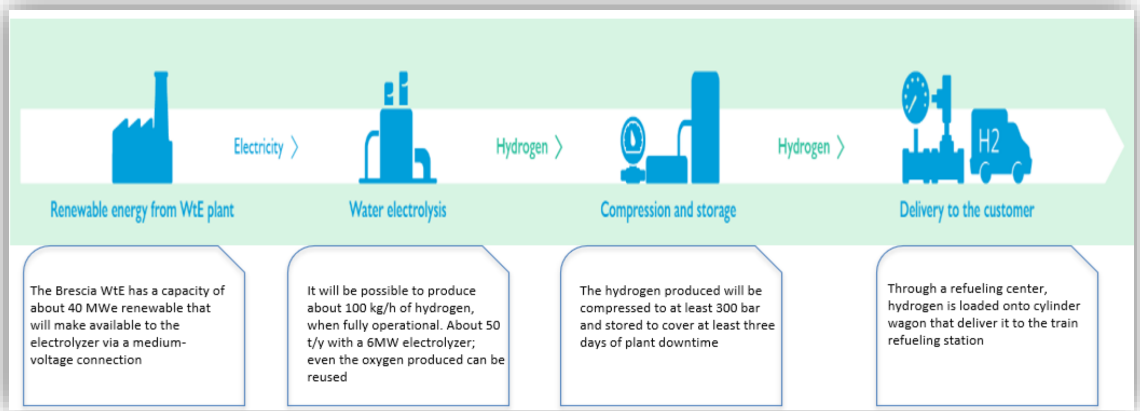


Figure 45 - How the plant works. Elaborated on a2a webpage image.

All this will come through the application of new technologies on the district: the 6 MW electrolyser linked to a WTE involved to the hydrogen production, new compression system (to store hydrogen at the production site), and a storage system functional to the distribution point (to allow refuelling station).

In the previous chapter, it was explained how the renewable energy used to power the electrolyser will be supplied by a2a Waste-to-Energy power plant of Brescia.

The site will produce a forecasted 830 ton per year of hydrogen, based on 43.870 MWh of electricity and 16.600 m^3 of water.

In order to fight climate change, the project reduces GHG emissions by using hydrogen produced from renewable energy sources instead of fossil fuels, storing hydrogen to uncouple production from consumption, and decarbonizing railway transportation by using hydrogen in place of fossil fuels.

H2Valcamonica project envisages several interventions that, combined between themselves, will make it possible to obtain the hydrogen needed for refueling rolling stock and more generally to act as a driver for the decarbonization of Valcamonica. In fact, now it is characterized by the presence of a dense industrial sector with high emissions (hard to abate).

4.3. The Hydrogen valley H2iseO - Hydrogen for Mobility

Valcamonica is a UNESCO world heritage site located in the east area of Lombardia Region, an important industrial pre-Alpine mountainous and lake area with a population of 120,000 inhabitants in the valley and of around 200,000 in the capital city in eastern Lombardy and a gateway to the 2026 Milan-Cortina Winter Olympics, along the non-electrified railway line Brescia-Iseo-Edolo. "H2iseO Hydrogen Valley" is a project carried out by FNM, Ferrovienord and Trenord, which aims to decarbonize public transportation services and encourage the transition to a more sustainable transportation system.

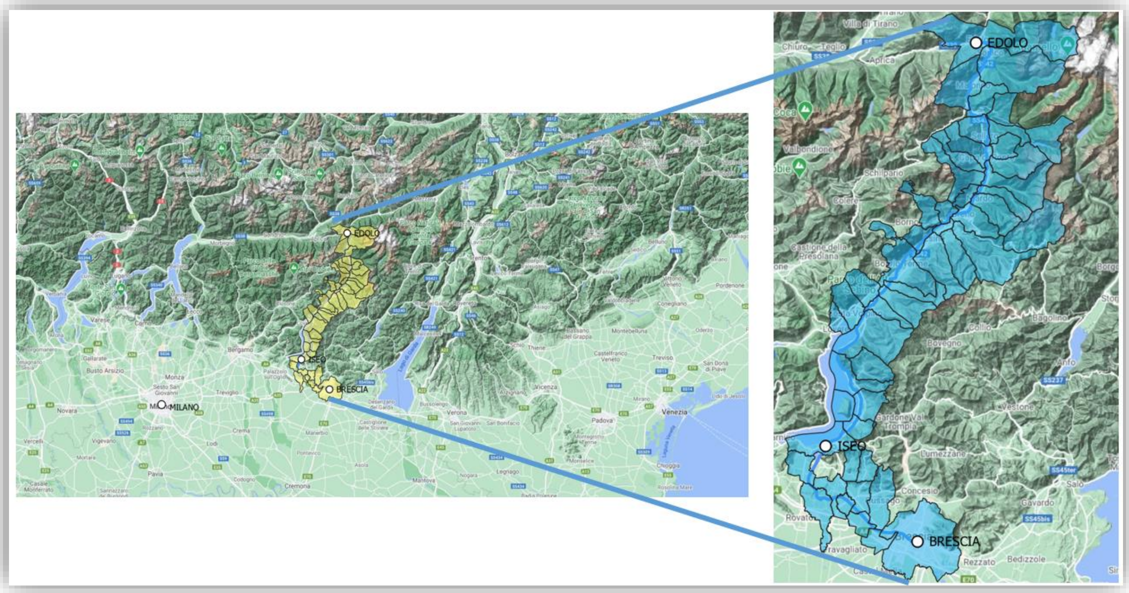


Figure 46 - The railway catchment area in Valcamonica: municipalities crossed by the railway line that will undergo the decarbonization process by replacing diesel-powered rolling stock with the new hydrogen-powered one.

The project is highly innovative and affects social, economic, geographic, and environmental dimensions of mobility, with three main objectives:

- development of a hydrogen-based economic and industrial district, starting with mobility applications;
- development of a geographic hydrogen-based district to enable and support energy conversion in the area;
- total decarbonization of the main components of local public transport.

Brescia-Iseo-Edolo railway line's "hydrogenization" and decarbonization, as the first consumer of hydrogen, enables the development of infrastructure for hydrogen production and delivery to assist the regional economy and industrial sector.
The complete list of the production, storage and distribution facilities will be:

- in Brescia a2a WtE (as explained in the previous paragraph about H2Valcamonica);
- in Edolo, from electrolysis, which will be able to generate about 1,400 KgH2/day;
- in Iseo: Steam Methane Reforming (SMR) technology from biomethane hydrogen production plant, coupled with storage and distribution plant and a CO_2 capture system, with a production capacity of an equal 1,400 KgH2 / day.

Sebino and Valcamonica will be the birthplace of the first Italian Hydrogen Valley as a result of the H2iseO initiative, which is supported by FNM, FERROVIENORD, and Trenord. Here there will be the introduction of hydrogen rolling stock as mentioned in the "*PNRR (National Recovery and Resilience Plan - M2C2.3 Promoting the production, distribution and end uses of hydrogen, Investment 3.4: Hydrogen Experimentation for Rail Transport*"). The total preliminary amount for the entire rolling stock fleet is over 160 million €.
Local public transportation will also use the hydrogen solution by 2025. Additionally, "green hydrogen" production and distribution facilities will be constructed. The total decarbonization of local public transportation is the ultimate objective.
The initiative is a first step toward establishing a hydrogen-based economic system as well as a zero-emission mobility system. Public mobility needs throughout the district will be met the introduction of a fleet of 14 rolling stock and 40 buses that will be powered by hydrogen.
The fleet of 40 buses enables the decarbonization of part of the bus service in Valcamonica as a pilot project in the area. [82]
The timeline of the project is represented in the Figure 47.

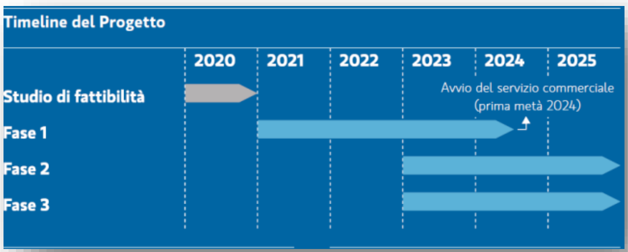


Figure 47 - Timeline of H2IseO project[82].

At present, the rolling stock are under construction and the design and construction permit for the hydrogen production and distribution facilities is underway.
Test runs will start in 2023 (Phase 1) and the beginning of the commercial service will follow in the first half of 2024 with the commissioning of six hydrogen rolling stock . At the same time, hydrogen production and distribution in Iseo will become operational.

Phase 2 will feature the commissioning of 8 more hydrogen trains, and the operation of the other production and distribution sites in Edolo and/or Brescia will be expanded, employing electrolysis technology from renewable energy.
Then, during phase 3, the commissioning of 40 hydrogen buses will take place and the design/implementation of hydrogen for other possible uses will see the light of day.
The H2iseO project begins with hydrogen demand (increasing demand as an off-taker) and integrates hydrogen production and distribution with a vertically integrated value chain. Hydrogen that is not needed for the project will be made available to other off-takers (including mobility service providers) through a horizontally integrated value chain.
FNM is considering the potential introduction of hydrogen refueling stations (HRS) along the motorway network for trucks, buses, and cars, connecting the project in the framework of the TEN-T network up to 2030. This would broaden the geographic scope of the H2iseO project, creating additional synergies and optimizing hydrogen production and distribution.[83]

GreenHyseO Project

As a component of the wider "H2iseO Hydrogen Valley" project, GreenHyseO takes into account the requirement for the development of several green hydrogen production facilities, as well as distribution and associated refueling stations.
Hydrogen production, storage, and distribution facility in the city of Iseo are specifically referred to as GreenHyseO. For this facility, Steam Methane Reforming (SMR) technology from biomethane will be used and it will also be able to capture and store the CO_2 produced thanks to the implementation of a CCS technology.
The Iseo hydrogen generation plant's CCS technology is the main focus of the GreenHyseO project. In particular, the initiative aims not only to manufacture hydrogen to power rail and bus fleets, but also to make the process "greener" by absorbing CO_2 and reducing greenhouse gas emissions significantly.
This project proposal is taking part in the InnovFund-SSC-2020 call for proposals as "GreenHyseO: hydrogen for sustainable mobility and circular energy in Valcamonica," and it has already received "project development assistance" from the EIB. A 72-month period is anticipated. FNM S.p.a. is the project's coordinator, while FERROVIENORD S.p.A. is its intended beneficiary.[83]

4.3.1. The role of Trenord in H2IseO

Trenord is the Railway Undertaking company entrusted with the service contract by the institutional body Regione Lombardia. It has to take care of all aspects related to the service: the rolling stock, its operations and maintenance. Trenord must also analyse the demand for mobility in the area concerned and plan the service offering with respect to this and other characteristics of the lines to be served.

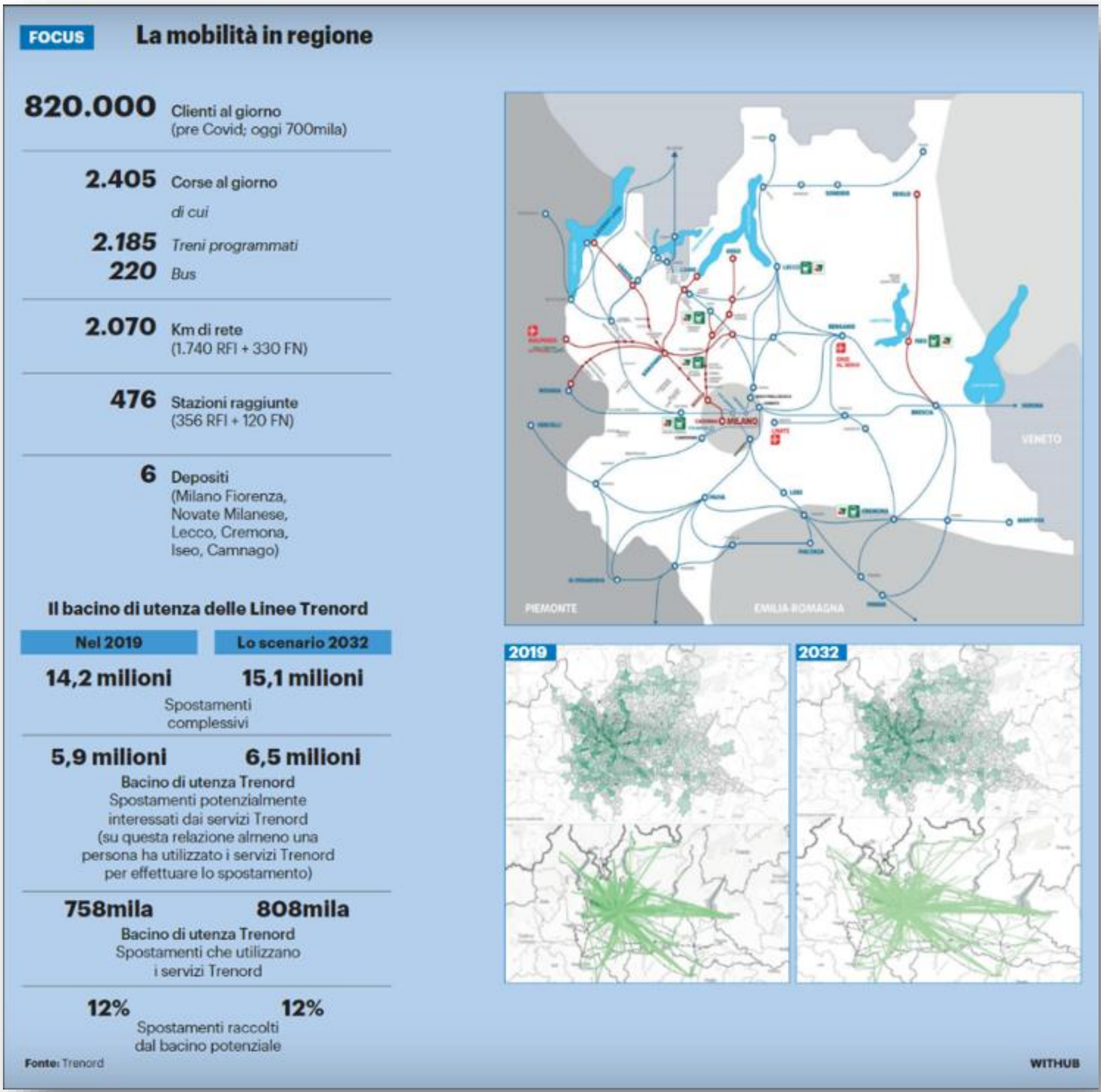


Figure 48 - Trenord Mobility data. Source: Il Giorno, 2022.

In the case of the Brescia-Iseo-Edolo line, it is planned, in tandem with the decarbonization project, to increase rail service that can be operated between 5:00 am and 11:00 pm, with hourly cadence and additional reinforcement at peak times, especially on the Brescia-Iseo section.

Trenord, through its commissioning and operational functions, will have the task of planning the replacement of old rolling stock, and through its engineering structure to introduce the new one with hydrogen technology with attention to meet all the requirements of the standards also with respect to the training and employment of operating personnel.
The first hydrogen rolling stock will be delivered to Trenord during 2023.
The fleet of 14 convoys enables the complete decarbonization of the Brescia-Iseo-Edolo railway line (in Valcamonica), which is currently served by a fleet of 14 diesel trainsets.

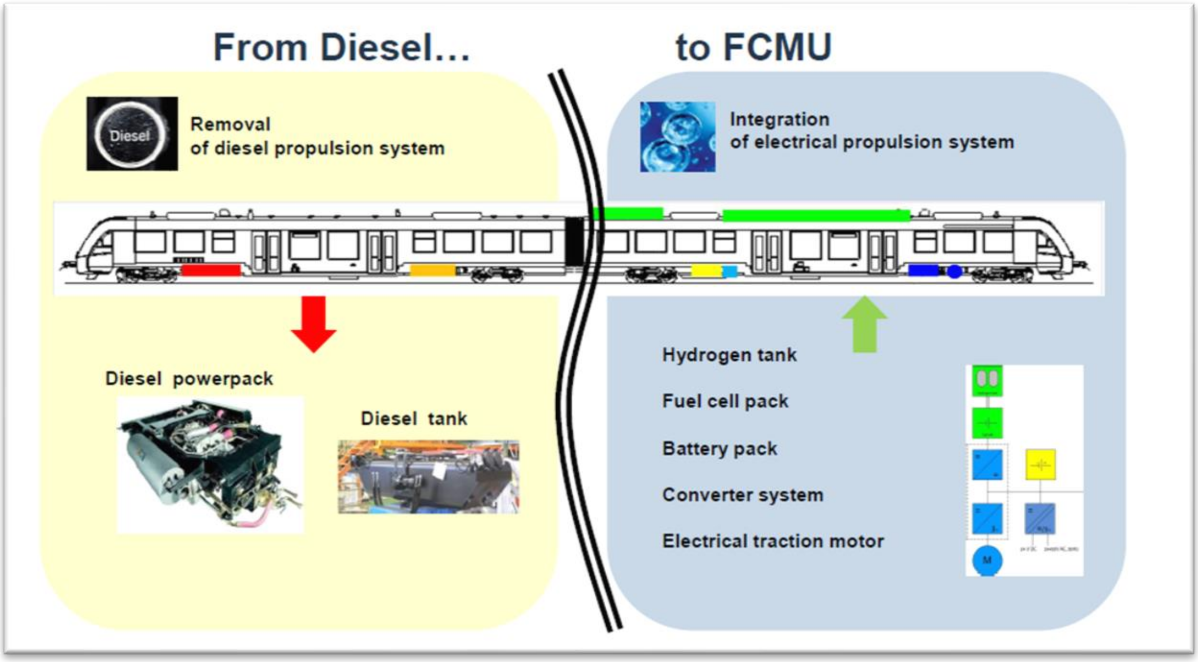


Figure 49 - Diesel vs FCMU configuration. Source: Alstom datasheet.

Figure 50 - Roling stock replacement. FCMU on the right. Souce: Alstom.

The 14 hydrogen fuel cell rolling stock will be supplied by Alstom to FNM, the main transport and mobility group in the Italian region of Lombardy, and then rented by Trenord.

The Alstom's Coradia Stream regional train platform, which is currently being constructed in Italy by Alstom's plant in Savigliano, will be used for the new rolling stock ' design. At Alstom's facility in Savigliano, project development, the majority of manufacture, and certification are carried out, while Bologna plant provides the on-board signalling systems.

The same fuel cell propulsion system that was made famous by the Coradia iLint (currently in commercial service in Germany) will be used in the hydrogen-powered

Coradia Stream for FNM. The range of hydrogen rolling stock will be comparable to that of diesel rolling stock.
The Coradia iLint is the first passenger rolling stock in the world to use a hydrogen fuel cell to provide traction power. Low noise levels are produced by this zero-emission train, which only produces steam and condensed water as exhaust. iLint is unique for its fusion of many cutting-edge components, including clean energy conversion, adaptable battery energy storage, and clever traction power and available energy management. It allows for efficient, environmentally friendly train operating while maintaining high performance standards because it was specifically created for use on non-electrified routes.

The infrastructure and areas dedicated to rolling stock maintenance, to date they are located in Iseo, adjacent to the station. A renovation of that depot is planned, and in addition, the area of the Rovato rail yard will probably be the subject of a new industrial settlement for maintenance dedicated to hydrogen vehicles.

4.3.2. The Rail Infrastructure

The infrastructural interventions planned by the Rail Infrastructure Manager Ferrovienord for the modernization of the non-electrified Brescia-Iseo-Edolo line are listed below. This line is directly related to the Hydrogen Valley project; such investments made by the infrastructure manager will bring technological innovations to the line itself [68] :

- <u>Hydrogen refueling rolling stock and operating vehicles in Iseo</u>
  A refueling station for rolling stock and service vehicles for railway use is planned.
  The plant, that feed three refueling stations, two of which are dedicated to rolling stock and one, along the road, for service vehicles for rail use.
  In addition, the plant will also be able to be powered by tank cars for which a special containment bay is planned.

- <u>Brescia-Iseo-Edolo line: upgrading of the Castegnato plant.</u>
  The upgrading to standard of the Castegnato station facility involves the resurfacing from the station's outer yard, the removal of architectural barriers, the resurfacing of the platforms and the construction of platform canopies to modernize the design and to bring the architecture in line with the new standards. In addition, there will be the construction of a bicycle-pedestrian underpass to bring benefit to soft mobility as well.
  At the track level, the track plan will be modified and consequently there will be an upgrade of the safety signalling system.

Finally, some mitigation works with increase of urban green will be planned.

- The Borgonato-Adro Plant
  This station will be subject to reconstruction and restyling: from the buildings to the railway platforms (with adjustment of the height from the rail height of 55 cm), barrier-free accesses to interventions related to soft mobility (bicycle-pedestrian); in addition, the modification of the track plan will be accompanied by the renovation with rehabilitation of the railway superstructure and also the adjustment of the signalling and safety system of railway traffic. The total estimated cost of the intervention at Borgonato-Adro is about 3.8 million euros.

- New Violino Station

  The intervention consists in the construction of a new railway stop at Violino, near Brescia. It will be characterized by the presence of two platforms with a length of 100 m and height adapted to the new standards to make access to trains easier and equipped with metal shelters to partially cover them. Also in this case, the aspect of accessibility to the facility is taken care of with barrier-free accesses, with pedestrian paths for the blind, consisting of specific raised flooring. This is complemented by a velostation with covered parking for bicycles. The total cost of this work is approximately 3 million euros.

5 Conclusion and future developments

The development of the hydrogen sector needs efforts to be deployed rapidly; the application of technologies, both the most proven and the most innovative in the market, must be strengthened by the applicability that instead is the result of adherent, rapid and dedicated regulatory interventions.
The realization of hydrogen value chain requires that there must be a proper assessment of the "scale of application" that from time to time will have to be adjusted. Technology and regulation are both in continuous research in terms of "winning spaces" . Maintaining an appropriate timeline to be truly effective is a delicate task and done synergistically between the scientific world and those responsible for establishing rules and regulations.
Only in this way there will be the transition to climate neutrality, bringing also significant opportunities, such as the potential for economic growth, new business models and markets, new jobs and technological development. Forward-looking research, development and innovation policies will play a key role.

Through the analysis of regulations, and particularly in investigating into the field inherent in hydrogen production, an attempt was made to narrow the framework of definitions with the aim of identifying what models are feasible to date to be compliant with the threshold values imposed for a hydrogen to be considered "renewable" or "clean" or "green."

The output of the analysis work has produced the following normative evidences:

- The Taxonomy delegated regulation sets the only indicator for whether a hydrogen production model is environmentally sustainable.
- The RED II directive indicates the characteristics of an energy source to be considered renewable and how it should be used

Following the model proposed by the current RED II Directive for the articulation of some constraints (additionality, etc..) related to the RFNBO for transport, and given the presence of a regulatory vacuum that was to be filled by the delegated act (precisely for the definition of "renewable hydrogen") , it was decided to bring back the very draft of the act in proposal, and which had been published last May 2022. In the drafting of the text in Chapter 3 are preceded by comparisons with what is in the UK legislation (which by analogy has the same starting points before the so-called Brexit in 2020).

Since then, after the consultation phase ended in June, the College of Commissioners should have formally adopted the text as amended, if any, thus leaving the Parliament and the Council to oppose it without the right to amend it. In the meantime, the introduction in Taxonomy (Reg 852/2020) of nuclear power as a sustainable source and some doubts about the principle of additionality have matured within the European Parliament to vote by a majority the amendment (AM10)[84] to the reform of RED II (RED III) that effectively trashes the principle of additionality for the transport sector.

Thus, the long-awaited definition of sustainable hydrogen has not come to fruition, and several stakeholders complain that this lack of "legal clarity" (in the presence of U.S. subsidies) undermines investment at the European level.

Regarding the case study addressed precisely on the applicability of the standards, it can be said that, to date, the proposed model of hydrogen production with the use of energy from Brescia a2a Waste-to-energy which has biogenic waste as its origin and therefore the guarantees of origin of the GSE. In Italy, is expressed as a virtuous model and is a candidate as one of the protagonists for future developments of value chains (Hydrogen Valleys).

The WTE model can express its effectiveness in the production of H_2 (also called Biohydrogen in chapter 3)which has the following characteristics:

- as Biogas, fits fully within the decarbonization path of the European energy system; it therefore falls within the calculation of the national contribution to the achievement of European renewable energy targets, and is therefore worthy of incentives;
- with respect to the threshold value stipulated in Section 3.10 of the European Commission's Delegated Regulation (EU) 2021/21397, the impacts of this type of hydrogen in terms of kilograms of CO_2eq emissions, calculated as recommended by the Delegated Regulation on Taxonomy using the LCA method, are 1.60 kg CO_2eq per kg H_2 produced, which is significantly lower than the threshold value of 3 kg CO_2eq/kg H_2.
  So this hydrogen has the following advantages:
  - according to Decreto del Ministero della Transazione Ecologica dated 21/09/2022 is definable as green hydrogen and meets the conditions for access to the facilities, which are the subject of the Decreto;
  - Is available immediately and is therefore able to help stably feed demand;
  - Would not be affected by the additionality principle specific to renewable fuels of non-biological origin (RFNBO).

Moreover, biohydrogen is produced with respect to keeping the load factor required by the electrolyser high for affordable hydrogen supply and put in place other advantages :

- ensures a stable flow of hydrogen in Waste-to-Energy plants that can reach a number of operating hours of nearly 8,000 heq/year. It also results in an optimized size for the hydrogen production plant (e.g., reduced storage);
- allows a reduction in the overall cost of production compared to technologies based on intermittent sources: the optimized utilization rate of the WtE plant is matched by a decrease in the cost of hydrogen production of at least 30 percent;
- the production makes use of electrolysis plants predominantly in "island" operation (except for circumscribed periods of emergency related to plant maintenance) that, in the future, can be easily enslaved directly to dedicated intermittent renewable sources or connected to the power grid to use via power supply agreement (PPA) the renewable energy in the system;
- in the ultra-mature phase also end-use hydrogen P2X.

Confirming all of the above is ARERA's resolution [70] of November 8, 2022 557/2022 , as application of the Decreto 21/09/2022, and already foreseen with the PNRR, which in fact takes note of the definition of green hydrogen and sets an intervention that incentivizes its production.

This type of hydrogen production, pending a more advanced development of the hydrogen market, and legislation that will perforce be increasingly stringent with more challenging emission containment targets, can therefore already play an important role in the decarbonization and independence path, being able to accelerate it.

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A Appendix - Acronyms

Acronym	Description
BEV	Battery Electriv Vehicle
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Usage and Storage
CO	Carbon Oxyde
CO_2	Carbon Dioxide
COP	Conference Of the Parties
ETS	Emission Trading System
EU	European Union
FCMU	Fuel Cell Multiple Unit
GHG	GreenHouse Gases
IPCC	International Panel for Climate Change
LNG	Liquid Natural Gas
LTS	Long Term Strategy
LULUCF	Land Use, Land Use Change and Forestry
MFF	Multiannual Financial Framework
Mtoe	Ega Tons of Oil Equivalent

NGEU	NextGeneratioEU
OECD	Organization for Economic Co-Operation and Development
PNIEC	National Integrated Energy and Climate Plan
PPM	Process and Production Method
PTE	Ecological transition Plan
PV	Photovoltaic
R&D	Research and Development
RED	Renewable Directive
RES	Renewable Energy Sources
RTFNBO	Renewable Liquid and Gaseous Transport Fuels of Non-Biological Origin
SCWG	Super Critical Water Gasification
SEN	National Energy Strategy
SGSW	Save Gas for Save Winter
TEN-E	Trans European Network for Energy

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Acknowledgments

To the memory of Daniela Fermi, the first to enlighten me on the path to hydrogen.

I want to thank the Advisor of this paper Prof. Renato Mazzoncini, for believing in the design of the work and for his ability in timing for innovation.

To Lorenzo Privitera, Co-Advisor and head of a2a's hydrogen unit, who accompany the research by laying the engineering foundations and tying them to feasible projects; to a2a's Regulatory Affairs working group for support in regulatory and for their humankind.

To Alessandro Borselli who, patiently, supported all the thesis work; and to Alberto Minoia first and Stefano Gervasini later, for giving all the support of Trenord Technical Management. To Stefano Erba for his support on the hydrogen issue from the FNM Group.

Thank you!

I thank all my family, friends and colleagues for always being been close by and for the understanding and encouragement they have never failed to provide. It would not have been possible without them.

Finally, I would like to thank everyone who will read this thesis: I hope it will be useful for you!