Replication scenarios pertaining to upstream systems. The view of the TSO

D5.3 – Public

HyPowerGT – Demonstrating a hydrogen-powered gas-turbine engine fuelled with up to 100% H2

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Abstract

This document provides a detailed outline of the methodology to be used for the techno-economic analysis related to the technology developed within the HyPowerGT project, with a focus on the "Upstream systems" case study. The techno-economic analysis, that will be developed in D5.2 (due date M42), includes a cost-benefit evaluation of the NovaLT16 H2 DLE installed at the compression station of the future hydrogen transport infrastructure

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Abbreviations and Acronyms

ACRONYM	DESCRIPTION
ATR	Auto-Thermal Reforming
B/C	Benefit-Cost Ratio
CBA	Cost Benefit Analysis
CCS	Carbon Capture and Storage

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CEF	Connecting Europe Facility
DLE	Dry Low Emissions
EE	Electric Energy
EGD	EU Green Deal
EHB	European Hydrogen Backbone
ENNOH	European Network of Network Operators for Hydrogen
ENTOSs	European Network of Transmission System Operators
EPP	Economic Payback Period
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gas Emissions
GWh	Gigawatt-hours
HHV	Higher Heating Value
HYUSPRE	Hydrogen Underground Storage in Porous Reservoirs
IEA	International Energy Agency
Kg	Kilogram
Km	Kilometer
LCOH	Levelized Cost Of Hydrogen
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
MTPA	Million tonnes per annum
NECP	National Energy and Climate Plan
NG	Natural Gas
NOx	Nitrogen Oxides
NPV	Net Present Value
NZE	Net Zero Emissions
PCI	Project of Common Interest
PEM	Proton Exchange Membrane
PINT	Put In One At A Time
PM	Particulate Matter

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PMI	Project of Mutual Interest
PNIEC	Piano Nazionale Integrato per l'Energia e il Clima (NEPC)
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RFNBO	Renewable Fuel of Non-Biological Origin
SCR	Selective Catalytic Reduction
SMR	Steam Methane Reforming
TEN-E	Trans-European Networks for Energy
TOOT	Take Out One at a Time
TSO	Transmission System Operator
TWh	Terawatt-hour
TYNDP	Ten Year Network Development Plan
UHS	Underground Hydrogen Storage

Executive summary

This report provides a comprehensive review of the technical and economic aspects of hydrogen transmission and storage infrastructure in the context of the evolving European hydrogen market, that will be considered for the development of the analysis related to the HyPowerGT technology, with a focus on the "Upstream systems" case study. Developed within the framework of Work Package 5 (WP5), specifically Task 5.2, the document focuses on contest in which the Dry Low Emissions (DLE) H2 combustion technology, specifically the DLE NovaLT16, will be evaluated across one of the three key replication scenarios: the upstream systems. The other two replication scenarios (i.e. industrial systems, and energy system solutions) will be analysed in D5.4 and D5.5, while the results of the three analysis will be included in D5.2.

Within WP5, Task 5.2 aims to systematically assess the technical merits and economic viability of integrating DLE NovaLT16 technology into the growing European hydrogen value chain. The report describes the methodology for evaluating DLE NovaLT16 as a potential core component of future hydrogen compression stations. These stations are crucial for providing the mechanical energy required for hydrogen compression and transportation through pipeline

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networks. The analysis addresses both the technical performance and the cost-benefit aspects of the technology, offering a methodological framework that will support further findings to be detailed in Deliverable D5.2 (scheduled for Month 42).

The report also explores broader hydrogen market development scenarios, summarizing current energy and hydrogen market trends, key policy frameworks, and targeted production cost benchmarks, that could impact the techno-economic analysis. These scenarios are informed by the latest data from European and international sources, ensuring relevance to policymakers, industry stakeholders, and project developers.

Overall, this deliverable positions DLE NovaLT16 technology as a promising solution for enhancing the efficiency and economic viability of hydrogen transmission infrastructure. By providing a detailed techno-economic evaluation and situating the analysis within the rapidly evolving European hydrogen landscape, the report aims to inform future investments and policy decisions. The methodologies and preliminary insights presented herein serve as a foundation for subsequent, more detailed analyses and recommendations that will be developed in upcoming project deliverables.

1. Objectives of the deliverable 5.3

D5.3 has been developed within the framework of WP5 and in particular Task 5.2 – Hydrogen techno-economic analyses. This task focuses on the evaluation of the DLE H2 combustion technology DLE NovaLT16 from technical and economic perspectives, considering three different case studies (also called replication scenarios):

- Upstream systems
- Industrial systems
- Energy system solutions.

In particular, D5.3 focuses on the first case study, where the DLE NovaLT16 is considered in relation to the developing European hydrogen market and the hydrogen transmission and storage infrastructure. This technology could potentially become the core system of the future hydrogen compression stations, providing mechanical energy needed to compress and move hydrogen through the pipeline network. Finally, the cost-benefit analysis methodology is introduced in order to evaluate the benefits of the proposed technology. The approach and methodology are here presented, while the results of the analysis will be then included in Deliverable D5.2, scheduled for Month 42.

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2. Hydrogen market development scenarios

The following paragraphs provide a picture of the energy and hydrogen market and policy development, together with the targeted hydrogen production costs.

2.1. Policy scenarios of energy and hydrogen market development

Hydrogen is a key component in the shift towards a fully decarbonised economy. Hydrogen produced via water electrolysis or other low-carbon emissions means (e.g. steam methane reforming + CO2 capture) can act both as feedstock for chemical or other industrial processes as it is globally recognised as capable of integrating renewable sources into the industrial and energetic system. This market shows promising applications across different sectors, including industrial processes, mobility and energy storage. According to the International Energy Agency's 2024 outlook, based on announced projects, global production of low-emission hydrogen could reach 49 Mtpa (1,633 TWh) by 2030[1]. On the demand side, the Agency foresees that hydrogen consumption should grow from the current 95 Mtpa (3,160 TWh) to more than 150 Mtpa (5,000 TWh) in 2030 in order to meet the Net Zero goal by 2050.

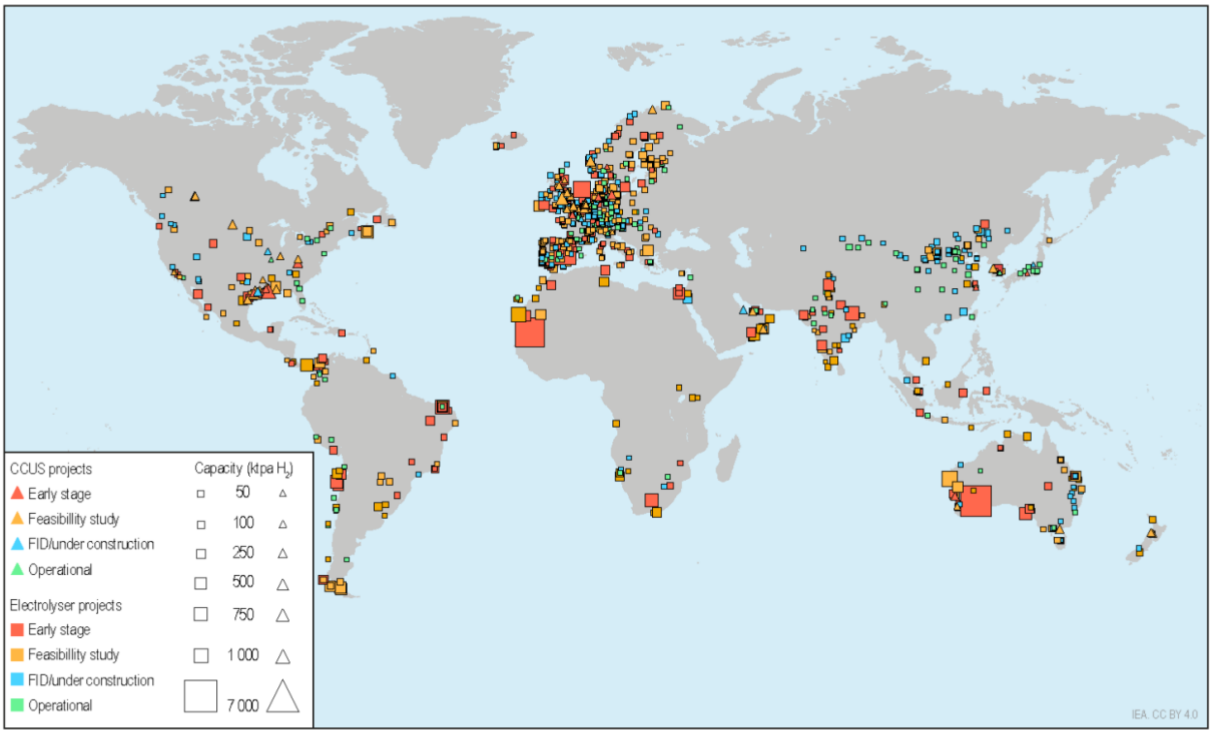

Figure 1: IEA Hydrogen Projects database (October 2024)

[1] International Energy Agency (IEA), *Global Hydrogen Review*, 2024 (website).

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According to the IEA, the number of low-emission hydrogen projects reaching final investment decisions has doubled in the past year, signaling growing investor confidence and accelerating market maturity. At the same time, technological progress and economies of scale are necessary to significantly reduce production costs, improving the competitiveness of low-emission hydrogen compared to fossil-based alternatives. These trends confirm hydrogen's readiness to play a central role in achieving a clean, integrated, and resilient energy future.

In the European Union, Hydrogen has been identified as one of the pillars of the REPowerEU plan. The European commission has set an indicative non-binding target of 10 Mtpa (333 TWh/y, LHV) of domestic hydrogen production and 10 Mtpa (333 TWh/y, LHV) of imported renewable hydrogen by 2030, as **local hydrogen production cannot meet the forecasted demand for clean H2[2].** The Ten-Year Network Development Plan (TYNDP) 2024 scenarios drafted by European gas and electricity Transmission System Operators (TSO) forecast a demand of 483 TWh/y (approximately 14.5 Mtpa, LHV) in 2030, of which around 180 TWh/y (5.4 Mtpa, LHV) coming from imports[3]. This reality underscores the **need for a transregional approach to connect lower cost production sites located across the EU and the neighboring countries with high demand areas of Central Europe**. In this scenario, hydrogen is not just a clean energy carrier, but also a strategic lever for energy security, competitiveness and industrial innovation.

Context and political priorities

The growing role of hydrogen within the European and Italian energy transition is part of a wider process aimed at reaching a series of objectives set across the years. Specifically, starting from the basis, the **Energy Union Strategy,** published in 2015, outlines the main EU energy policy objectives in the EU contemporary energy policy framework. It is based on five pillars: energy security, internal energy market, energy efficiency, decarbonisation, and research & innovation[4]. In June 2019, the final elements of the **Clean Energy for All Europeans Package[5]** (or Clean Energy Package) were adopted, shaping today's European energy system and greatly influenced the hydrogen sector. This set of legislation aims to implement the goals of the Energy Union strategy, facilitating Europe to move away from fossil fuels and make the transition toward cleaner energy, and deliver on the EU's Paris Agreement commitments for reducing greenhouse gas emissions.

[2] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, *REPowerEU Plan,* 2022 (website)
[3] ENTSOG, ENTSOE, *TYNDP 2024 scenarios report,* 2025 (website)
[4] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank, *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy,* 2015 (website)
[5] European Commission, Clean energy for all Europeans, 2019.

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Flanked by the Directive 2003/87/EC, the **EU Emission Trading System (ETS)** is another key energy policy instrument that complements the legislative framework defined in the Clean Energy Package and meant to help the EU reach its decarbonisation targets.

Within this context, the European Green Deal proposal was presented by the Commission in December 2019 as a policy roadmap meant to be "the EU's new growth strategy". This announcement builds on political momentum as climate issues gained significant saliency across the EU, and it marks a shift in the EU energy policies from the Energy Union, where decarbonisation was just one of five pillars, to a growth pathway totally focused on sustainability. As the first of the European Commission's twin priorities (together with the digital transition), it aims to enable the green transition, to introduce a political and legislative framework to reach climate-neutrality by 2050 and it provides both the strategy and the means to achieve Net Zero Emissions (NZE).

In July 2020, the European Union enacted the **European Hydrogen Strategy**[6] paving the way to establish a clean hydrogen market. The adoption of the Strategy testifies the high level of commitment of the European Commission in developing a structured legal framework including all the different elements of the hydrogen value chain: production, transport, distribution, storage, end-uses (e.g. mobility, heat&power) and cross-cutting topics.

The European Hydrogen Strategy has laid the foundations for a **Clean Hydrogen Sector.** As Figure 2 shows, fundamental policy documents were issued based on the EU Green Deal and the Hydrogen Strategy.

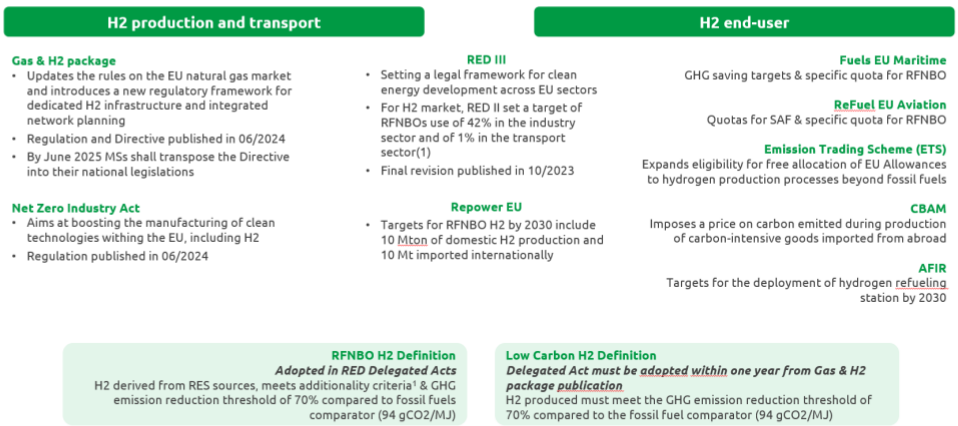

Figure 2: European Union policy framework for hydrogen (Source: Hydrogen Europe)

The goals set out in the EU Green Deal (EGD) were written down in the **EU Climate Law Regulation,** which gave a primary saliency to the role of hydrogen to the targets. **It has been the first time that green and low-carbon hydrogen have officially been cited as a way out of the fossil fuel economy in a binding legal text[7].**

[6] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, *A hydrogen strategy for a climate-neutral Europe*, 2020 (website)

[7] European Parliament, Council of the EU, *European climate law,* 2021 (website)

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Furthermore, the Commission presented its **"Fit-for-55" package**, a set of policy proposals preparing the implementation of the EU Green Deal, aiming at completely overhaul key climate, energy, and transport legislation to reach its ambitious climate objectives for 2030 and 2050. Fit-for-55 aims to reduce greenhouse gas emissions (GHG) by at least 55 percent by 2030 (compared to 1990 levels) and it includes binding targets for the uptake of renewable hydrogen in industry and transport by 2030[8]. In December 2021, the **"Hydrogen and Decarbonised Gas Market" package** was announced with the objective to support the creation of a dedicated infrastructure for hydrogen and as well as an efficient hydrogen market (including low-carbon hydrogen); the package has been published in June 2024[9].

This comprehensive package includes a Directive and Regulation, which underwent negotiation between the European Council and Parliament throughout 2023, resulting in a final provisional agreement. Considering the contingency situation, to rapidly reduce the EU's dependence on Russian fossil fuels, in May 2022 the European Commission presented the **REPowerEU Plan**, which aims to accelerate and complement several ongoing EU legislative initiatives. In particular, it addresses the "Fit-for-55" package by raising several targets, such as the target for renewable energy (from 40% to 45%). Hydrogen has been identified as one of the six components of this effort and the Commission has devoted an entire section of the REPowerEU to hydrogen, setting an indicative, non-binding target of 10 Mtpa (333 TWh/y, LHV) of domestic hydrogen production and 10 Mtpa (333 TWh/y, LHV) of imported renewable hydrogen by 2030.

In February 2025 the European Commission published the **Clean Industrial Deal**[10] where it confirmed the central role of hydrogen in decarbonising our EU energy system, in particular in the hard to abate sectors. To support European hydrogen objectives the European Commission allocated €3 billion to the domestic production of hydrogen through the European Hydrogen Bank mechanism. The initiative is funded from the revenues generated by the European Emission Trading System (ETS) and takes the form of an auction, whereby bidders receive a subsidy to bridge the price gap between their production cost and the market price for hydrogen, currently led by non-renewable sources. The pilot auction was launched in 2023 and granted a fixed premium for renewable hydrogen production within the EEA for 10 years. The results of the second auction have been published in May 2025 and the Clean Industrial Deal confirm a third call of the European Hydrogen Bank in Q3 2025 with a budget of up to EUR 1 billion, to de-risk and accelerate the uptake of hydrogen production in the EU.

Along with European policymakers' work to support and regulate the nascent hydrogen market, research groups and industrial associations have engaged in forecasting the expected future hydrogen demand under different energetic, economic and weather scenarios. As already mentioned, European electricity and gas transmission systems operators (ENTSOs) have included hydrogen demand in their joint energy scenario forecasting. This activity is key

[8] Council of the European Union, *Fit for 55,* (website)
[9] European Commission, *Hydrogen and decarbonised gas market,* (website)
[10] European Commission, *Clean industrial deal,* (website)

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as basis for the development of the ten-year network development plan (TYNDP). TYNDP 2024 forecasts that in 2030 the European H2 demand (not including captive onsite production) will reach 483 TWh[11] and is projected to increase to 1700-2200 TWh by 2040, depending on the scenario considered. As shown in Figure 3, this demand will predominantly come from industrial players for both energetic and non-energetic uses. Specifically, 67% of H2 demand in 2030 and approximately 40% in 2040 will come from industrial players, and another significant share will be demanded to produce e-fuels.

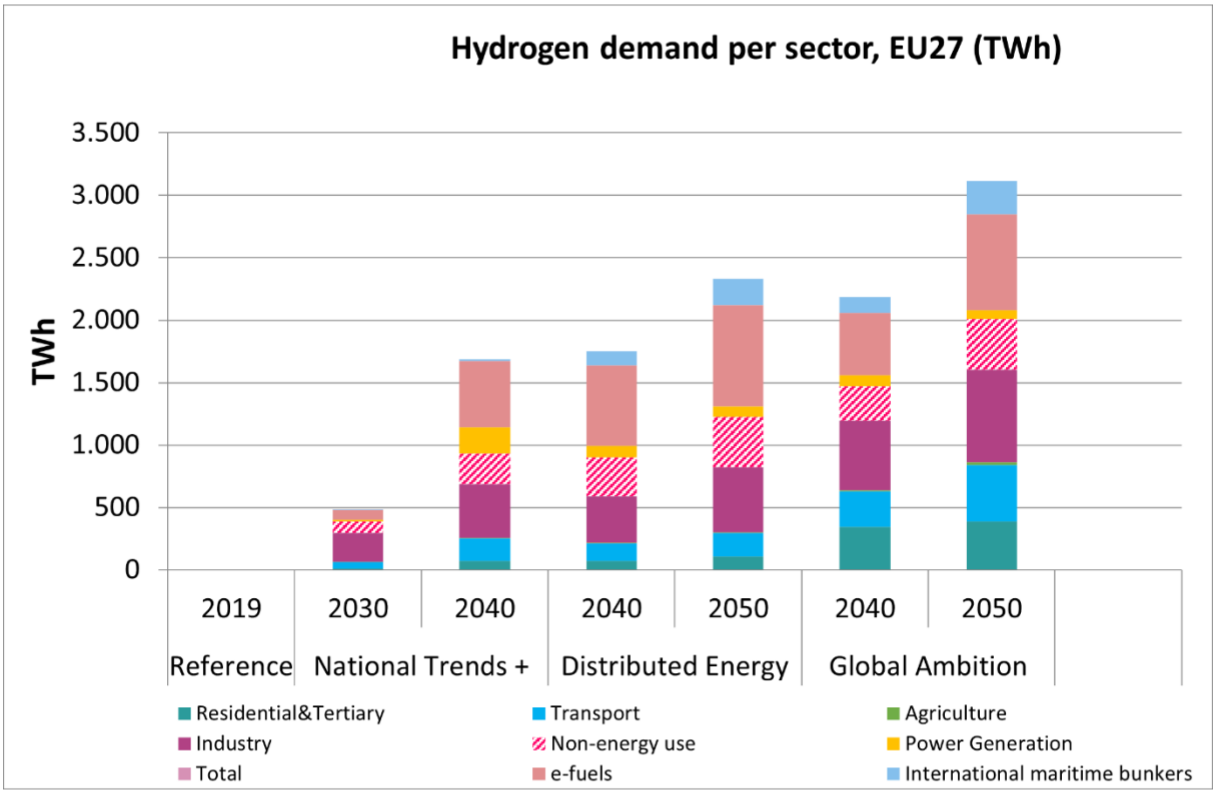

Figure 3: Hydrogen demand per sector, EU 27 (TWh)

In addition to European-level policy planning, several European Member States have identified their potential hydrogen national demand in their National Energy and Climate Plans (NECPs) and National Hydrogen Strategies. For example, Germany estimated a national hydrogen demand between 95-130 TWh/y (2.9-3.9 Mtpa) in 2030, of which 50-70% covered by import[12]. France has recently updated its national H2 strategy, foreseeing a consumption of 520 kton (approximately 17 TWh LHV) of H2 in 2030[13].

Concerning Italy, the NECP foresees an H2 consumption of 0,25 Mton (8,4 TWh) in 2030, of which 46% expected from the industrial sector and the remaining from mobility (including aviation and sea mobility)[14]. The National H2 Strategy instead adopts a longer-term

[11] ENTSOG-ENTSOE, TYNDP 2024 – Final Scenarios Report, January 2025 (website).
[12] Federal Ministry for Economic Affairs and Climate Action (BMWK), *National hydrogen strategy update*, July 2023
[13] French H2 Strategy update (website)
[14] Ministero dell'Ambiente e della Sicurezza Energetica, *Piano Nazionale Integrato per l'Energia e il Clima*, 2024 (website)

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perspective to 2050, analysing in greater detail the sectoral distribution of H2 uses. The document foresees that H2 demand will range between 74 and 139 TWh in 2050, more than half of which coming from the transport sector (particularly heavy-duty vehicles and aviation). Another 25-30% of this demand will come from the industrial sector, led by the steel industry and uses as feedstock. On the supply side, at least 30% up to 80% of the production needed to satisfy this demand will come from imports[15].

From a TSO perspective, the most recent energy scenarios published for Italy (Snam-Terna 2024 scenarios) estimate 4-8 TWh (aligned with PNIEC) for renewable H2 in 2030, while the forecast for 2040 ranges between 59 and 92 TWh[16].

2.2. Expected H2 production cost

A decisive factor in determining the adoption of H2 will be its availability at a competitive cost for the end user. As of today, the two main alternatives for low-carbon H2 production are water electrolysis and methane reforming with CO2 capture.

2.2.1. Renewable Hydrogen and Electrolysis Technologies

Renewable hydrogen is generated through the electrolysis of water, a process in which electricity is used to split water molecules into hydrogen and oxygen. While commonly referred to as “green hydrogen” when powered by renewables, the EU’s formal definition under the Renewable Energy Directive (RED III) and its Delegated Acts is more specific. Hydrogen qualifies as renewable—formally, as a Renewable Fuel of Non-Biological Origin (RFNBO)—if the electricity used comes from renewable sources directly, or from the grid under strict conditions of temporal and geographical correlation and is backed by Guarantees of Origin from renewables[17].

Two main electrolysis technologies are commercially available today: **alkaline electrolyzers** and **proton exchange membrane (PEM) electrolyzers**. Alkaline systems, which rely on liquid electrolytes such as potassium hydroxide, are the most mature and widely deployed. They operate at relatively low temperatures and are best suited to steady-state industrial applications. PEM electrolyzers, on the other hand, use a solid polymer membrane and offer higher current densities, faster response times, and better load flexibility, making them ideal for integration with variable renewable energy sources. However, PEM systems are typically more expensive due to their use of noble metals like platinum and iridium, and they require very high-purity water.

[15] Ministero dell’Ambiente e della Sicurezza Energetica, *Strategia Nazionale idrogeno*, novembre 2024 (website)
[16] Snam-Terna, *Documento di descrizione degli scenari,* 2024 (website)
[17] European Commission, *Renewable hydrogen*, (website)

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The efficiency of these technologies is comparable, generally ranging from 60% to 70% based on the higher heating value of hydrogen[15]. The choice between them depends on the specific use case, scale, and operational profile.

2.2.2. Blue Hydrogen: A Transitional Approach

Blue hydrogen is produced from natural gas through processes such as **steam methane reforming (SMR)** or **auto-thermal reforming (ATR)**, in which hydrogen is extracted from methane. These processes inherently produce carbon dioxide, but when combined with **carbon capture and storage (CCS)** systems, a significant portion of the CO_2 emissions—typically between 60% and 95%—can be avoided. Although blue hydrogen is not emissions-free, it represents a viable **transitional solution** to rapidly scale up hydrogen availability while renewable-based systems develop further.

Blue hydrogen benefits from the existing gas infrastructure and offers a relatively low cost of production. However, its long-term sustainability is debated due to methane leakage risks, the energy penalty associated with CCS, and dependency on fossil feedstocks.

2.2.3. Cost Perspectives and Economic Viability

The cost of hydrogen production varies substantially depending on the pathway, input prices, and project scale. Hydrogen produced via **SMR without carbon capture**—commonly referred to as *grey hydrogen*—is currently the cheapest option, with production costs typically ranging between **€1.5 and €2.0 per kilogram**[18]. However, this cost advantage is expected to erode over time. As the **EU ETS** tightens, the **carbon price will increasingly affect grey hydrogen**, given its high CO_2 intensity. In addition, Europe's strong dependence on **imported natural gas** undermines long-term cost stability and energy autonomy, making grey hydrogen particularly exposed to external market shocks.

These same vulnerabilities extend—albeit partially—to **blue hydrogen**, which is produced from natural gas through SMR or ATR combined with **CCS**. Although blue hydrogen reduces direct CO_2 emissions, it remains linked to fossil inputs and therefore **subject to ETS-related cost increases**, especially in configurations with incomplete capture. Blue hydrogen currently exhibits production costs in the range of **€3.0 to €4.0 per kilogram**[18]**,** depending on natural gas prices and the capture efficiency of the chosen technology.

In contrast, **electrolytic hydrogen**—produced by splitting water using electricity—is presently more expensive, but costs are **declining rapidly**. The most critical determinant of the cost of electrolytic hydrogen is the **price of electricity**, which can account for more than two-thirds of the total production cost. Under favorable conditions—for example, a power purchase agreement at €40/MWh and high electrolyzer utilization—a PEM-based system may produce hydrogen at a cost as low as **€4.5 per kilogram**[18]. However, the actual cost is highly sensitive to variables such as the electricity sourcing model (e.g., grid vs. off-grid renewables),

[18] Ministero dell'Ambiente e della Sicurezza Energetica, *Strategia Nazionale idrogeno*, novembre 2024 (website)

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electrolyzer CAPEX, load factor, and system size. For these reasons, it is not meaningful to assign a single figure to green hydrogen without contextualizing the assumptions behind the estimate.

The **Italian National Hydrogen Strategy** (2024) provides benchmark estimates that reflect this variability. In the case of **hydrogen imported from North Africa via pipeline**, the total levelized cost — including transport — is estimated at approximately **€4.4 per kilogram**. This scenario benefits from the superior solar and wind conditions in North Africa and the cost-effectiveness of pipeline transport over long distances. Conversely, domestic production through **large-scale electrolyzers** powered by renewables within Italy results in significantly higher costs, estimated at least **€8.0 per kilogram**. This is primarily due to higher domestic electricity prices, lower full-load hours, and reduced economies of scale.

Further insight into cost dynamics comes from the **European Hydrogen Bank**, a financial instrument created by the European Commission to accelerate renewable hydrogen deployment by **bridging the cost gap** between green and fossil-based hydrogen. Through competitive auctions, the Hydrogen Bank awards fixed premium contracts per kilogram of renewable hydrogen produced, funded via the EU Innovation Fund.

The second auction round, concluded in 2024, revealed substantial heterogeneity in **levelized cost of hydrogen (LCOH)** across Europe. Participating projects declared cost ranges between approximately **€5.5 and €11.1 per kilogram**[19], depending on factors such as regional electricity prices, project scale, electrolyzer efficiency, and renewable energy availability. These figures highlight the ongoing challenge of achieving cost parity with conventional hydrogen and the continued need for targeted public support mechanisms to enable large-scale market rollout.

3. Role of transport and storage infrastructure in the H2 market

Chapter 3 explores the crucial role of transport and storage infrastructure in the development of the hydrogen economy. It compares various hydrogen transport options—from pipelines to road and maritime solutions—highlighting their respective advantages and challenges. The chapter details the emergence of a pan-European hydrogen network, focusing on flagship initiatives like the European Hydrogen Backbone and European Projects of Common Interest. It also analyses the significance of large-scale underground hydrogen storage, both in porous reservoirs and salt caverns, for balancing supply and demand. Finally, the chapter addresses the strategic use of hydrogen blending in natural gas networks, emphasizing how these diverse

[19] European Commission, *IF24 Auction,* (website)

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approaches collectively enable a resilient, flexible, and efficient hydrogen market across Europe.

3.1. Advantages of pipeline transport vs other transport modes: costs comparison

To have a fully developed hydrogen market a combination of diverse transport technologies must be considered. This includes various modes of transport—**road, rail, pipeline, and ship**—as well as different physical and chemical states of hydrogen, such as **pure hydrogen, blended hydrogen, or hydrogen carriers**. The choice of technology will depend not only on the volumes to be transported but also on the distances to be covered, ranging from **local to national and intercontinental transport,** as shown in Figure 4.

For shorter distances and smaller volumes, road transport is a common and flexible solution. Specifically, **compressed gaseous hydrogen cylinder trucks** are best suited for short distances, while for longer distances, it's more **cost-effective** to transport larger volumes using **tanker trucks with cryogenic tanks (Liq-H2)** or **aluminium tanks (LOHC)**. When very large volumes and consistent demand are present, dedicated **hydrogen pipelines** offer the most efficient and economical long-haul transport. Furthermore, for intercontinental trade, **shipping** of liquid hydrogen or hydrogen carriers like **ammonia (NH3)**, which boasts a high hydrogen content, is emerging as a crucial option, enabling global supply diversification despite the energy-intensive conversion processes involved. The burgeoning hydrogen economy necessitates continued innovation across all these transport modalities to optimize cost, safety, and efficiency.

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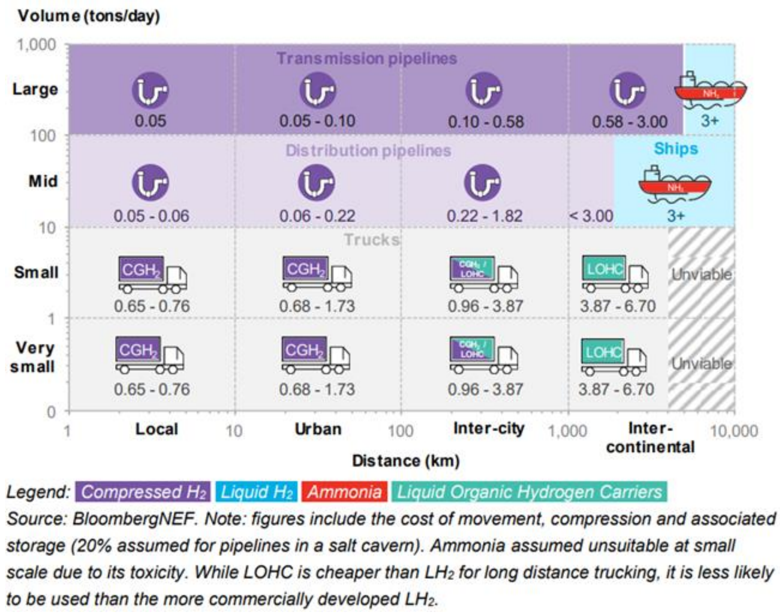

Figure 4: Hydrogen transportation cost for various distances and carriers [20]

3.2. Development of a European H2 infrastructure

The development of a European market for renewable and low-carbon hydrogen aligned with the EU targets requires large-scale production, which is likely to be located in areas that are distant from consumption sites, as:

1. Multiple countries require electrolysers to be co-located with their renewable energy source for hydrogen to be considered renewable in compliance with EU rules (RED II delegated acts);
2. The areas with the highest renewable energy potential (Southern European regions, North Africa, the Baltic Sea) tend to be distant from the industrial end users both within the same country and in neighboring countries.

Furthermore, even countries that have or are expected to have a low-carbon electricity grid in the near future (e.g. Norway, Sweden) and can therefore choose the preferred location for the electrolysers are expected to export their surplus H2 production to larger industrial economies, particularly Germany.

This geographical asymmetry requires the development of large-scale infrastructures to transport the produced volumes to the consumption sites. Such infrastructures entail a high level of technical and economic complexity, therefore bottom-up and top-down initiatives have developed to coordinate and facilitate the H2 infrastructure-planning process at the European level, in particular:

- The European Hydrogen Backbone (EHB);
- Hydrogen Projects of Common Interest (PCI), promoted by the European Commission;

[20] BloombergNEF, *Hydrogen economy outlook,* 2020 (website)

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- The European Network of Network Operators for Hydrogen (ENNOH).

Along with the broader European development plan each TSO has detailed its own infrastructure project, either as part of a broader European Corridor (e.g. the Italian Hydrogen Backbone as part of the SoutH2 corridor) or as a project mainly directed at serving national demand (Hydrogen Core Network in Germany).

With the aim of developing an integrated European hydrogen transport system in the long term, the **EHB initiative** was launched in 2020. The initiative currently involves the cooperation of 33 gas transport operators from 28 European countries, envisioning a Europe-wide hydrogen transport network to be implemented through a combination of upgrading existing infrastructure and constructing new pipelines.

The 2022 preliminary "H2 infrastructure vision and coordination" exercise has gathered crucial data[21] related to key infrastructure corridors concerning:

i. **Re-utilization of existing gas assets (repurposed assets):** For example, Corridor A, which includes Italy, anticipates a repurposing share of approximately 60% of total assets, making it the corridor with the highest repurposing rate. This has a positive impact on the cost of infrastructure development.

ii. **Proximity to energy storage sites:** Such as depleted fields or salt caverns, to support the corridor's seasonal and daily flexibility needs for the benefit of consumption points.

iii. **Proximity to production and consumption sites along the corridor.**

The **Report**[21] outlined five pan-European corridors for hydrogen supply and import by 2030: North Sea, Nordic & Baltic, Eastern, North Africa-Italy, Southwest Corridor. These corridors will connect industrial clusters, ports, and Hydrogen Valleys to regions with abundant hydrogen production.

The study included detailed transport cost assessments. Transporting hydrogen over **1,000 km along the proposed onshore backbone** was estimated to cost, on average, **€0.11-0.21 per kg of hydrogen**, making the EHB the most economical option for large-scale, long-distance hydrogen transport. If hydrogen is transported via offshore pipelines, the cost would be **€0.17-0.32 per kg of hydrogen transported for 1,000 km.** These estimates relied on the cost ranges shown in Table 1:

Values in €M/km	**Onshore**	**Offshore**
New	1,4-3,4	3,4-5,8
Repurposed	0,2-0,6	0,3-0,6

Table 1: cost per km for new and repurposed H2 pipelines (EHB, 2022)

[21] European Hydrogen Backbone, *A European hydrogen infrastructure vision covering 28 countries,* 2022 (website)

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Due to the persistent cost increases following raw materials' rising prices and global supply chain disruptions, these values have been revised upwards. These trends are already captured in 2023 EHB's cost update[22], as show in Table 2:

Values in €M/km	**Onshore**	**Offshore**
New	1,8-4,4	5,4-7,5
Repurposed	0,5-0,9	1,1-1,5

Table 2: costs per km for new and repurposed H2 pipelines (EHB, 2023)

As shown in paragraph 2.1, these cost changes are compounded by uncertainties over the future development trajectory of the hydrogen demand and supply market, and by the complexity inherent to the realisation of infrastructure projects stretching for thousands of km. In 2022 the European Commission has therefore extended the policy support instrument of Projects of Common Interest (PCI) to the hydrogen sector ("new TEN-E" Regulation EU 2022/869). PCIs are initiatives recognized as strategic at the European level, aimed at improving the development of the EU energy market, focusing on supply security, and accelerating the decarbonization of the energy system. PCIs focus on key cross-border infrastructure projects, and PCI status could help overcome economic, technical and regulatory barriers. The PCI mechanism involves a biennial selection process based on specific criteria such as market impact, contribution to the EU's climate goals and improvements in energy security. Selected projects have the following benefits:

- Accelerated planning and permit granting, helping projects move faster through often complex administrative procedures;
- A single national authority responsible for granting all necessary permits within a strict maximum timeframe of 3.5 years;
- Improved regulatory conditions, including incentives and rules for the allocation of costs across borders;
- Lower administrative costs due to streamlined environmental assessment processes, simplifying compliance while ensuring environmental protection;
- Increased stakeholder engagement through formal consultations, enhancing transparency and support from local communities, regulators, and other stakeholders;
- Greater visibility to investors, which helps attract financing and private sector interest;
- PCIs (and Projects of Mutual Interest, PMIs) have the right to apply for funding from the **Connecting Europe Facility (CEF)**, an EU financial instrument dedicated to supporting infrastructure projects that promote EU energy policy objectives.

In 2023, the first list of hydrogen PCIs under revised TEN-E regulation was approved, including 65 projects spanning from H2 pipelines to storages, ammonia import terminals and electrolysers. These projects (represented in Figure 4 below) will constitute the core of the

[22] European Hydrogen Backbone, *Implementation roadmap — cross border projects and costs update*, 2023 (website)

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future H2 infrastructure development[23] and can be grouped according to EHB's proposed corridors.

Figure 5: PCI Transparency Platform – Projects Approved under the VI list[23]

Each of the PCI-approved projects constitutes are integrated in broader national and multi-national H2 infrastructure development plans. For example, the Italian and Austrian PCIs are jointly part of the SoutH2 Corridor, a 3,300 km dedicated hydrogen pipeline corridor potentially able to import Hydrogen from North Africa (up to 4 Mtpa at full development) and transport it across Italy, Austria and Germany[24].

German TSO are currently developing one of the most advanced hydrogen networks in Europe (German hydrogen Core Network). The project foresees the development of a 9.040 km hydrogen infrastructure, leveraging on both local production and import (estimated approximately 101 GWh/h entry capacity) to provide a domestic exit capacity of 87 GWh/h[25].

[23] European Commission, *Projects of Common Interest and Projects of Mutual Interest interactive map,* (website)
[24] *The SoutH2 Corridor* (website)
[25] FNB Gas, *Hydrogen Core Network,* (website)

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3.3. Role of large-scale Underground H2 Storages in the H2 economy

As hydrogen becomes increasingly integrated as an energy carrier, large-scale storage solutions are essential to ensure continuity, seasonal balancing, and system flexibility. In this context, **Underground Hydrogen Storage (UHS)**—particularly in **porous reservoirs**, such as depleted gas fields and deep saline aquifers—emerges as a key technology for the stable and resilient operation of a hydrogen-based energy system.

The European project **HyUsPRe** (Hydrogen Underground Storage in Porous Reservoirs) has carried out an in-depth assessment of the technical, economic, and environmental feasibility of such solutions, providing a concrete vision for their deployment by 2050.

3.3.1. Seasonal Hydrogen Storage and European Geological Potential

Underground storage systems enable the storage of large volumes of hydrogen over extended periods (from weeks to entire seasons), contributing significantly to balancing intermittent renewable production with variable energy demand. According to projections by HyUsPRe, **Europe could require up to 270 TWh of hydrogen storage capacity by 2050**, with more than half potentially provided by porous reservoirs[26].

This storage capacity avoids over-dimensioning of electrolysers and transport infrastructure, supporting a more efficient and scalable integration of hydrogen into the energy grid.

HyUsPRe mapped Europe's geological resources for hydrogen storage, revealing many depleted gas fields and deep aquifers accessible through existing pipelines and compressors, enabling cost-effective and faster deployment. Europe currently has **over 400 TWh of underground natural gas storage** in porous reservoirs, much of which could be repurposed for hydrogen after compatibility checks.

HyUsPRe's experimental and modeling work (WP1 and WP2) found no major technical barriers to underground hydrogen storage (UHS). While risks like hydrogen migration, rock interactions, and microbial activity exist, they can be managed through careful site selection, hydrogen-compatible materials, continuous monitoring, and specialized well designs. These results support full-scale pilots such as Austria's EUH2STARS, one of Europe's first UHS demonstrations in porous rock. HyUsPRe outlines a roadmap with five pillars—technology scaling, environmental management, economic sustainability, regulatory alignment, and stakeholder

[26] HyUSPRe (Hydrogen Underground Storage in Porous Reservoirs), *EU-scale hydrogen system scenarios,* 2024 (website)

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engagement—to enable widespread UHS deployment in Europe by 2030–2050, emphasizing its role in seasonal flexibility, energy security, and cost-effective use of existing infrastructure.

3.3.2. Salt Caverns for Hydrogen Storage

In addition to porous reservoirs, **salt caverns** represent a well-established option for underground hydrogen storage, characterized by artificial cavities created through solution mining in deep salt formations. Unlike porous reservoirs, where hydrogen is stored within the pore spaces of natural rock formations, salt caverns provide a large, sealed void space that can be rapidly filled and emptied, enabling **highly flexible and fast cycling operations**.

This flexibility makes salt caverns particularly suitable for **short-term storage and daily or weekly balancing needs**, complementing the seasonal and large-scale storage capacity provided by porous reservoirs. However, salt caverns generally have **smaller storage volumes**, typically on the order of a few hundred gigawatt-hours (GWh), compared to the terawatt-hour (TWh) scale of porous reservoirs.

Europe's salt cavern capacity is concentrated mainly in regions with extensive salt deposits, including northern Germany, the Netherlands, the United Kingdom, Poland, and parts of France. The total volume of salt caverns available for gas storage in Europe is estimated to be around **20–30 TWh equivalent** (natural gas basis), with some existing facilities already repurposed or considered for hydrogen storage projects. Despite the limited geographical distribution, the operational advantages of salt caverns—such as low cushion gas requirements and fast injection/extraction rates—make them an important complement in the European hydrogen infrastructure landscape.

In summary, while **porous reservoirs provide large-scale, seasonal hydrogen storage capacity**, **salt caverns offer operational flexibility and rapid response**, and they are both essential components for a resilient and efficient hydrogen economy.

Finally, it's worth mentioning that another type of underground storage facility, "Mined, Lined Rock Caverns," could play a key role in future hydrogen infrastructure as a solution for intra-day storage and to support linepack management in hydrogen transport networks. However, the only existing small-scale pilot project in this regard is the private HYBRIT project, while public data and studies are still lacking on this topic.

3.4. Role of blending as an enabler

In an initial phase of market development, characterized by limited hydrogen demand and the absence of a pure hydrogen infrastructure that could connect production centers in the South with hydrogen demand centers in the North, a significant contribution can come from using natural gas and hydrogen blends. **H2-NG blending** allows for the utilization of existing gas infrastructures and reduces the transportation costs of produced hydrogen, also enabling

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optimized production (in geographical areas with higher renewable productivity and larger scale).

Current legislation in Italy already allows the injection of up to **2% hydrogen** into the gas grid[27], and the same percentage is allowed at cross-border interconnections across Europe[28]. With limited plant modifications, it's possible to use hydrogen blends of up to **20% by volume** in industries, particularly in hard-to-abate sectors, and for civil uses.

4. Role of H2 DLE combustion technology for Compression Stations (Transport and Storage)

This section describes the technological features and advantages of the NovaLT16 H2 DLE gas turbine.

4.1. Description of H2 DLE combustion technology for upstream system applications

Hydrogen pipelines are very much on the horizon—and in some regions, they're already becoming a reality. Europe is leading the charge with ambitious plans, like the European Hydrogen Backbone. Globally, over 30,000 km of hydrogen pipelines are in development, with more than 90% of existing infrastructure located in Europe and North America.

In this evolving infrastructure, hydrogen-fueled gas turbines play a pivotal role since they can provide the mechanical energy needed to compress and move gas through the pipeline network and they are often preferred over electric motors for driving centrifugal compressors in gas pipelines because they do not require a connection to the electrical grid. Instead, they can be fuelled directly by the gas flowing through the pipeline, in this case hydrogen, making them highly self-sufficient. This is especially advantageous in remote areas, where establishing a reliable electrical connection can be technically challenging and cost-prohibitive.

When designing gas turbines to drive centrifugal compressors in hydrogen pipeline systems, several critical technical requirements must be met to ensure safety, efficiency, and regulatory compliance. One of the foremost requirements is that the turbine must be capable of operating on up to 100% hydrogen fuel.

[27] G.U. n. 139 del 16-06-2022
[28] Gas and Hydorgen Package 2024/1788 - 2024/1789

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Another essential feature is the ability to start up directly on 100% hydrogen. This eliminates the need for a dual-fuel system or a natural gas supply during startup, which is particularly important in hydrogen-dedicated infrastructure or in remote locations where natural gas may not be available. The capability to operate and start up with fuel containing hydrogen up to 100% has been designed and patented on the NovaLT16 H2 configuration: this existing product configuration, equipped with a combustion system based on partial premixing technology is the starting point of the product evolution from a high NOx combustor moving toward the 25 ppm NOx emission target of the H2 DLE combustor. The capability to start up with fuel containing hydrogen up to 100% is part of the H2 DLE technology development.

The gas turbine shall be designed to minimize NO_x emissions, which are a significant environmental concern. Therefore, the NovaLT16 H2 configuration need to be provided with an SCR in order to abate NOx emission down to the value that matches the local regulation.

Installing a Selective Catalytic Reduction (SCR) system on a gas turbine in a compression station can be particularly challenging due to several practical constraints. First, gas turbines in pipeline stations are always operating in open cycle mode: this makes the installation more complex and less efficient compared to combined cycle setups. Additionally, many compression stations are located in remote and unmanned areas, which introduces logistical difficulties. SCR systems require a continuous supply of urea or ammonia to function properly, and in isolated locations, regular refilling and maintenance can be problematic. Without on-site personnel, ensuring the timely replenishment of these reagents becomes a significant operational burden, potentially compromising the reliability of emissions control.

While the NovaLT H2 product already has got a 100% hydrogen start-up capability, the DLE technology adds a combustion system capable to abate NOx and match local regulation, without the need of installing an SCR. This is the real enabler for GT DLE deployment in hydrogen pipelines.

4.2. Key advantages of NovaLT16 H2 DLE technology

4.2.1. Technical advantages

The aim of the technology development of the H2 DLE combustion is to provide the largest fuel flexibility to the NovaLT16 H2 gas turbine, already proven for the partial premixing technology, while further reducing the NOx emission down to the typical normative limits existing for the natural gas (25 ppm). The challenge to be addressed, providing a full air-fuel premixing with hydrogen can enhance the emission performances of the gas turbine, while maintaining the start-up and operability capability already proven for the NovaLT16 H2 product. Instrumental to successfully obtain the H2 DLE combustion goal, will be the design and verification of other ancillary technologies based on combustion acoustics control and management.

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4.2.2. Environmental advantages

The capability of the NovaLT16 H2 DLE technology to handle any fuel composition from pure natural gas to pure hydrogen is a fundamental advantage to minimize the environmental impact of the power transformation realized by the gas turbine. Such fuel flexibility is supporting the energy transition phase, allowing the introduction of the available hydrogen as fuel in incremental percentage to the natural gas (standard fuel for existing infrastructures). Pure hydrogen combustion removes completely the CO2 source, primary GHG source with claimed impact on the Earth global warming. In addition, the low NOx technology (H2 DLE) will combine the zero carbon emission of the hydrogen fuel with a substantial reduction of NOx emission down to the typical normative limits existing for the natural gas (25 ppm): NOx emission, even if not been a GHG, still are claimed to be responsible of acid rain and to be harmful for the human health.

4.2.3. Economic advantages

Assuming the typical scenario of gas turbine operation within typical normative limits existing for the natural gas (25 ppm), the NovaLT16 H2 DLE technology can significantly reduce the LCOE with respect to the existing NovaLT16 H2 product configuration, by removing the CAPEX of an SCR asset and, most affecting, by removing the OPEX of the urea or ammonia required supply for the SCR operations, since the fully premixed combustion technology removes the need of a NOx emission abatement in the exhaust gas line.

5. Cost-Benefit Analysis

This chapter outlines the methodology and principles for conducting Cost-Benefit Analyses (CBA) of energy infrastructure projects, with a particular focus on gas and hydrogen networks. It explains the objectives of CBA, such as market integration, security of supply, environmental sustainability, and service quality. The text details the steps for quantifying costs and benefits, describes relevant economic indicators, and highlights the importance of scenario analysis. Finally, it addresses the unique aspects of CBA applied to hydrogen projects, including the evaluation of environmental and market impacts.

5.1 What is the CBA

The CBA (Cost-Benefit Analysis) is a methodology for evaluating projects that aims to capture not only the economic impact but also the broader welfare effects of an investment. In the

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field of energy infrastructures, CBA is a crucial tool for the Regulators' approval or rejection of new projects.
The key elements currently included in CBAs for natural gas infrastructure projects in Italy are summarized below.

Objectives of Projects Subject to CBA

In Italy, a gas network infrastructure development project must in the first place specify the objectives it aims to achieve, which may include the following[29]:

1. **Market Integration**: Actions aimed at improving the functioning of the energy market and reducing consumer costs.
2. **Security of Supply**: Initiatives designed to ensure the availability and continuity of energy supply.
3. **Competition and Diversification of Supply Sources**: Projects that increase diversification and competition among energy sources as well as among operators in the gas market.
4. **Methanization of Unserved Areas and Meeting New Demand**: Expansion of natural gas infrastructure to areas not currently served and support for emerging energy needs.
5. **Environmental Sustainability**: This includes projects that reduce environmental impacts (CO_2 and other pollutants) and support the decarbonization of the energy sector — for example by switching from more polluting fuels to natural gas or reducing methane leakage. It also includes the integration and development of renewable and low-carbon gases (e.g., biomethane, synthetic methane, blue and green hydrogen) into the Italian energy system.
6. **Service Quality**: This includes initiatives that aim to improve the quality of service to meet the needs of network users and stakeholders more generally, for example by ensuring service continuity, reliability, and high safety standards.

5.2 Methodology for Conducting a Cost-Benefit Analysis

The cost-benefit analysis process is structured into the following phases[29]:

1. **Identification of benefits**, which must be direct and endogenous to the energy sector, expressed in quantitative terms (i.e., determining the quantitative impact on the system resulting from the implementation of the project).
2. **Monetization of the benefit** through the application of specific coefficients expressed in €/unit (representing prices, avoided costs, etc.).

[29] Snam Spa, *Criteri applicativi dell'Analisi Costi Benefici per gli interventi di sviluppo della rete di trasporto*, (website)

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3. **Quantification of the estimated costs** of the project, including both capital expenditures (CAPEX) and operational expenditures (OPEX).
4. **Calculation of key economic performance indicators**:

   a. **Net Present Economic Value (NPV)**: the present value of the benefits and costs generated by the project over the period of analysis.
   b. **Benefit-Cost Ratio (B/C)**: the ratio between the present value of benefits and the present value of costs generated by the project over the analysis period.
   c. **Economic Payback Period (EPP)**: the time required for the cumulative discounted benefits to exceed the cumulative discounted costs.
5. **Sensitivity and risk analysis**, to assess the robustness of results under different assumptions or scenarios.
6. **Identification and description of quantitative and qualitative benefits** associated with the project that are not directly monetizable.

5.3 System Development Scenarios

To assess benefits resulting from the implementation of a project scenarios concerning demand, supply, and infrastructure availability are developed[29].

For each year of the analysis period, the benefits are calculated starting from a reference infrastructure network as the difference between a simulation in which the project is implemented and a counterfactual in which the project under evaluation is not implemented.

Regarding the evolution of demand and supply, the most recent available scenarios are used, including the **Snam-Terna scenarios** for Italy and those developed at the European level by **ENTSOG** and **ENTSO-E**. These scenarios take into account factors such as:

- macroeconomic and social trends,
- the potential emergence of new supply sources,
- technological development,
- demand elasticity with respect to price and income variables.

Regarding supply sources availability specifically, the following elements are considered within the supply scenarios:

- the capacity and availability of various supply sources;
- demand needs under the different scenarios;
- the evolution and availability of infrastructure at the European level;
- the price levels of different energy sources.

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5.4 Economic Analysis

The economic analysis identifies the benefits and costs associated with the implementation of the infrastructure project.

To ensure transparency and comparability, monetary benefits and costs are evaluated in real terms, using prices referenced to the Ten-Year Development Plan's base year. The analysis assumes a **4% real discount rate**, **a 25-year operational horizon**, and **no residual value** beyond that period.

The Net Present Economic Value (NPEV) of the project represents the discounted cash flow of the difference between the benefits and the costs of the intervention. It is calculated using the following formula:

$$VAN_E = \sum_{t=f}^{c+24} \frac{(B_t - C_t)}{(1+s)^{t-n}}$$

Where:

- B_t: expected monetary benefit for the system in year *t*
- C_t: expected total cost in year *t*, CAPEX and OPEX
- *f*: the first year in which costs for the project are incurred or forecasted
- c: the first year of full operation of the project
- *n*: reference year of the CBA (usually the Ten-Year Development Plan year)
- *s*: real discount rate

The Benefit-Cost Ratio (B/C) is the ratio of the present value of the benefits to the present value of the costs of the intervention. It is calculated as:

$$\frac{B}{C} = \frac{\sum_{t=f}^{c+24} \frac{B_t}{(1+s)^{t-n}}}{\sum_{t=f}^{c+24} \frac{C_t}{(1+s)^{t-n}}}$$

This ratio is a measure of the social utility of the project, intended as **social welfare generated per unit of capital invested**. A project with a positive social impact should demonstrate a B/C>1.

The **Economic Payback Period (EPP)** is the time needed for cumulative discounted benefits to surpass cumulative discounted costs. It serves as a proxy for evaluating the project's ability to generate net economic gains, indicating how quickly the investment becomes economically viable.

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5.5 Benefit Estimation Methodology

The analysis for benefit calculation is performed for each individual project by comparing the behavior of the system with and without the implementation of the project (the so-called *incremental approach*) within the reference scenario for the year under consideration.

The benefits are assessed relative to a reference infrastructure network that does not include the implementation of the project under evaluation, while including any other planned investments that would have been carried out regardless, due to regulatory obligations or authoritative requirements.

The **incremental approach** adopted is either the **PINT method** (*Put IN one at a time*) or the **TOOT** (*Take OUT one at a time*). According to PINT the incremental benefit is calculated by adding the project to the counterfactual scenario and assessing the impacts relative to that configuration. The TOOT methodology instead calculates the incremental benefit by removing the project compared to the counterfactual situation.[30]

Only the benefits within the region in scope — i.e., those corresponding to the area bearing the costs of the intervention—are taken into account. Any benefits accruing to **other countries** are, where possible, reported for informational purposes only, but are **excluded from the economic analysis**.

5.6 Application to Hydrogen Projects

In February 2025, **ENTSOG** published the CBA methodology for hydrogen infrastructure and electrolyzers. Given the currently limited development of hydrogen infrastructure in Europe, this methodology will initially apply to **projects applying for PCI or PMI status**, or to existing PCIs/PMIs involved in **funding request procedures or cost allocation processes**.

The rules follow many of the principles outlined for gas CBAs. As in the previously described cases, the estimation of benefits is carried out over a **25-year time horizon** using a **4% real discount rate** and assuming a **zero residual value** beyond the analytical horizon.

On the cost side, both **CAPEX and OPEX** of each intervention are considered. The key performance indicators (KPIs) are again the **Net Present Economic Value (NPEV)** and the **Benefit-Cost Ratio (B/C)**.

A crucial aspect of the CBA methodology is the definition of the scenarios used. For hydrogen-related projects, ENTSOs scenarios are evaluated.

[30] ENTSOG Methodology for Cost-Benefit Analyses of Hydrogen Infrastructure Projects (2025, website)

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In order to define the scope of the CBA, it is necessary to consider not only the specifics of the hydrogen scenario but also potential developments in the electricity (EE) and methane (CH_4) sectors, including their possible interactions.

5.7 Classification of Hydrogen Project Benefits

Below is a list describing and classifying the potential benefits associated with hydrogen projects[30]:

- B1 – Reduction of CO_2 Emissions (GHG):
  Change in emissions related to the production process and energy generation required for the process itself. Emissions from import phases of the value chain are also considered. The net change in CO_2 emissions is monetized at the social cost of carbon;
- B2 – Reduction of Non-CO_2 Emissions (e.g., NOx, PM):
  Non-CO_2 emissions from the same processes considered in B1. The health benefits related to avoided emissions are monetized.
- B3.1 – Integration of Renewable Energy Sources (RES) Generation:
  Evaluation of the TWh of RES electricity integrated into the energy system as a result of the project.
  → This benefit is not monetized.
- B3.2 – Integration of Renewable and Low-Carbon Hydrogen:
  Assessment of the increase in renewable or low-carbon hydrogen integrated into the system as a result of the project.
  → This benefit is not monetized.
- B4 – Socio-economic welfare generated by the Infrastructure:
  Quantification of economic surpluses resulting from the project. These surpluses can involve multiple actors across the value chain:
  - Producer side: sale price and marginal cost;
  - Consumer side: willingness to pay and actual price;
  - Export side: exported volumes and export prices;
  - Cross-sectoral impacts;
  - Injection and withdrawal prices in storage facilities.

  → All these elements contribute to monetizable economic surpluses.
- B5 – Reduction in Unserved Hydrogen Demand:
  Comparison between the demand unserved with and without the project during stressful conditions. The value is determined by multiplying the difference of unserved demand with and without the project by the **cost of disrupted H_2** and the **probability of an adverse event**.

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Conclusion

The analyses conducted in this document highlight the centrality of hydrogen as a key energy carrier in the transition towards a more sustainable and resilient energy system. By evaluating various scenarios (chapter 2), it becomes clear that the gradual integration of hydrogen can contribute not only to the decarbonization of industrial and transport sectors, but also to strengthening the security and flexibility of energy networks.

The role of dedicated infrastructure (chapter 3) is crucial for enabling large-scale deployment of hydrogen, both in terms of production and in terms of distribution and storage. In this context, the DLE NovaLT16 technology (chapter 4) stands out as a technological innovation, offering advanced solutions for the efficient and reliable use of hydrogen, with tangible benefits in terms of performance and emission reduction.

Applying the Cost-Benefit Analysis methodology (chapter 5) will be possible to evaluate, from both a technical and economic perspective, the overall impact of introducing the new solutions proposed by the HyPowerGT project. The analysis considered not only direct benefits—such as the reduction in unserved hydrogen demand and the monetizable economic surpluses for different value chain actors—but also cross-sectoral impacts and the system's resilience under stress conditions.

The results, which will be detailed in deliverable 5.2, will provide a comprehensive overview of the effectiveness of the adopted approach including also the replication scenarios which will be described in deliverables D5.4 and D5.5 (Industrial systems, Energy system solutions). In conclusion, the integration of the described technological solutions and infrastructures not only enables new development opportunities for the hydrogen value chain, but also represents a fundamental step towards a safer, more innovative, and sustainable European energy system.

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