Hy2Market

Integration of green hydrogen into an industry in Italy

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Executive Summary

The Hy2Market Sicilian pilot represents one of the most advanced real world demonstrations of how green hydrogen can be integrated into an existing industrial energy system. Implemented at the Duferco industrial site in Giammoro, Sicily, the project brings together an ecosystem of industrial partners and research institutions with the shared objective of validating a complete hydrogen value chain, from renewable hydrogen production to its final use in a 58 MW peaker gas turbine.

At the heart of the initiative is the deployment of De Nora's 1 MW Dragonfly® alkaline electrolyzer, a containerized and fully integrated system capable of producing around 200 Nm³/h of high purity hydrogen at 29 bar, with a specific energy consumption of 53.7 kWh per kilogram of hydrogen produced. The electrolyzer is supported by its own water treatment and purification units and is fed by a 20,000 liter water reserve, ensuring operational continuity even under suboptimal water supply conditions. The hydrogen is first collected in a 1.6 m³ buffer tank and then directed to a dedicated oil free piston compressor that increases its pressure from approximately 29 bar to 200 bar, allowing the gas to be stored safely in six high pressure cylinders capable of accommodating around 202 kg of hydrogen. These components are housed within reinforced concrete bunkers designed according to ATEX and fire prevention regulations to ensure safe operation in all phases of the process.

Once produced and stored, the hydrogen is injected into the natural gas supply line feeding the Siemens SGT A65 WLE peaker turbine. A static mixer installed along the fuel line enables a homogeneous blend containing up to 15% hydrogen by volume, a concentration selected to balance combustion stability, environmental benefits, and compatibility with existing turbine hardware. As a dispatch oriented plant, the turbine operates under the instructions of the Italian transmission system operator Terna, providing fast response balancing services essential for a grid increasingly dominated by intermittent renewable energy sources. The introduction of hydrogen into this context makes the pilot particularly relevant, as it demonstrates hydrogen's ability to decarbonize flexible power generation, one of the most challenging segments of the energy system to electrify.

A major component of the project is the extensive permitting, safety engineering, and compliance work coordinated by Duferco. The plant's design adheres to the most recent Italian fire prevention regulations for hydrogen production and storage, including the Ministerial Decree of 7 July 2023, and to ATEX and PED directives governing explosive atmospheres and pressure equipment. The hydrogen production facility does not require an Environmental Impact Assessment, nor is an Integrated Environmental Authorization necessary under the new European directive, given its modest production capacity. Detailed safety distance analyses, structural designs compliant with

NTC 2018 seismic standards, and a comprehensive risk evaluation framework ensure that the plant operates within the highest safety margins.

CNR ITAE has complemented these engineering activities with a simplified combustion modelling performed using COMSOL Multiphysics. By simulating both natural gas operation and a 15% hydrogen blend, the study demonstrated that the model reproduces trends consistent with real turbine data, providing a reliable interpretation of the environmental impact of hydrogen integration. The results show clear benefits: NOx emissions decrease by about 13%, carbon monoxide by nearly 39%, and carbon dioxide by almost 9%, while turbine outlet temperature drops by more than 5%. These improvements are achieved without compromising combustion stability, thanks also to controlled water injection within the turbine. The modeling confirms that even modest hydrogen blending can yield meaningful decarbonization effects in high flexibility gas turbine systems.

With detailed engineering completed and component manufacturing scheduled to conclude by February 2026, installation is expected to proceed by late spring of the same year. The Hy2Market Sicilian pilot thus stands as a strategic milestone for both Sicily and Europe. It demonstrates not only the technical feasibility of hydrogen natural gas co firing in industrial scale turbines but also the regulatory, infrastructural, and operational pathways needed to replicate similar installations in other industrial clusters. SNAM’s involvement further enhances the project’s strategic depth, providing guidelines for extending the model to regional gas networks, petrochemicals, and refineries, and contributing to the vision of a Sicilian Hydrogen Valley aligned with the goals of REPowerEU.

1. Introduction

The Hy2Market Sicilian pilot represents a strategic initiative aimed at demonstrating the practical integration of green hydrogen into an existing industrial energy system within the Italian context. Hosted at the Duferco industrial site in Giammoro (Sicily), the project brings together industrial partners and research institutions to develop and validate a complete hydrogen value chain, from renewable hydrogen production, via a 1 MW electrolyzer to its compression, storage, and blending with natural gas for use in a 58 MW peaker gas turbine. This pilot has been conceived to address the growing need for flexible, low-carbon power generation in energy systems characterized by increasing shares of intermittent renewable sources, while offering a replicable blueprint for hydrogen adoption in other industrial applications.

The activities carried out under Hy2Market involve coordinated technological, regulatory, and engineering efforts. Duferco provides the industrial site and leads the permitting, design, and integration of hydrogen into the existing power plant. De Nora contributes its electrolysis technology, supplying the containerized Dragonfly® system for on-site hydrogen production. Power Evolution designs the hydrogen compression, storage, and blending systems, ensuring operational reliability and safety. SNAM evaluates the potential adaptation of gas infrastructure to hydrogen and explores replicability scenarios, while CNR-ITAE develops system modelling, optimization, and scientific support, acting as coordinator of the Sicilian pilot.

By integrating hydrogen production with grid-balancing power generation, the project aims to assess both technical feasibility and environmental benefits. The pilot will enable real-world evaluation of hydrogen–natural gas combustion, verify emissions reductions, and provide crucial insights into the scale-up of hydrogen technologies and their compatibility with existing infrastructures. Ultimately, the Hy2Market Sicilian pilot contributes to regional and European strategies for decarbonization, supporting the implementation of REPowerEU targets and positioning Sicily as an emerging hub for hydrogen-based industrial innovation.

The document describes how hydrogen production, compression, storage and blending with natural gas are implemented to supply a 58 MW peaker gas turbine, creating one of the first real industrial demonstrations of hydrogen use in flexible power generation. The report outlines the roles of the partners involved, including Duferco as industrial host and system integrator, De Nora as supplier of the 1 MW Dragonfly® electrolyzer, Power Evolution as designer of the compression and storage systems, SNAM as infrastructure expert, and CNR-ITAE as scientific coordinator responsible for system modelling.

The text details the characteristics of the site, the regulatory context governing hydrogen installations, and the permitting pathway required to build and operate the pilot plant, highlighting compliance with ATEX, PED and fire-prevention legislation. It then illustrates the full engineering design of the hydrogen production facility, describing the water treatment system, the electrolyzer performance, the buffer tank, the high-pressure compressor, the storage cylinders, the blending station and the associated electrical and control systems. Safety considerations are central throughout the report, with extensive discussion of risk analysis, safety distances, gas detection, ventilation, emergency procedures and structural protections.

A substantial section is dedicated to combustion modelling performed with COMSOL Multiphysics, where the turbine’s behaviour is simulated using natural gas and a mixture containing 15% hydrogen. The modelling methodology, chemical kinetics and assumptions are explained, followed by validation against real plant measurements. Results show that hydrogen blending reduces NOx, CO and CO_2 emissions and lowers the turbine outlet temperature, confirming the environmental benefits of introducing hydrogen into peaker-plant operations.

Overall, the document offers a detailed and structured account of the design, safety, regulatory and scientific activities behind the Hy2Market Sicilian pilot, demonstrating its relevance as a replicable model for hydrogen integration in industrial energy systems.

2. Hy2Market Sicilian pilot overview

Topics covered in this chapter:

- Preliminary overview of the Sicily Pilot
- Role and strategy of the partners involved in the pilot
- Activities planned in Hy2Market

2.1. Introduction

The Sicilian pilot within Hy2Market involves four companies and one research institution. The companies play a key role in developing an industrial plant that integrates:

- hydrogen production through a 1 MW electrolyzer (De Nora);
- hydrogen compression, storage (200 kg), and blending with natural gas (Power Evolution);
- use of a hydrogen–natural gas blend in a 58 MW gas turbine operating as a peaker unit in the Italian power system (Duferco).

Duferco hosts the pilot at its Giammoro plant and provides industrial leadership in integrating hydrogen into the peaker turbine. Its role ensures that operational results on hydrogen utilization are directly linked to industrial needs, creating a strong business case for hydrogen substitution of natural gas in power generation. De Nora, a global leader in electrochemical technologies, supplies the 1 MW pilot electrolyzer. Their involvement ensures the production of high-quality hydrogen and advances electrolysis technology for industrial-scale applications. Power Evolution is focusing on the optimization of hydrogen compression, storage, and blending, assessing efficiency and quality aspects. They play a key role in designing the entire plant. SNAM, the Italian Gas Transmission System Operator, will explore how existing infrastructure in Sicily can be repurposed to accommodate hydrogen, with a particular focus on replicating the business case in industries such as refineries and petrochemicals. Their experience in large-scale hydrogen initiatives, including IPCEI projects, strengthens the regional and European relevance of the pilot. The research institution CNR-ITAE (Consiglio Nazionale delle Ricerche – Istituto di Tecnologie Avanzate per l’Energia) contributes scientific expertise in system integration, optimization, and demonstration. CNR-ITAE is modelling the whole energy conversion chain of the Sicilian pilot and delivers valuable insights on operation, management, and scaling-up for replication in other industrial contexts. CNR-ITAE acts as the coordinator of the Sicilian pilot, supporting design activities and developing modeling and simulations related to blend combustion and techno-economic optimization of the whole energy conversion.

2.1.1. Duferco

Duferco is an industrial group historically active in the steel sector and in the trading of raw materials, and progressively diversified into the energy, services, and logistics sectors. The Group’s structure is currently organized through several operating and coordinating companies, each covering specific business lines at an international level.

Since 2010, Duferco has managed an integrated portfolio of energy assets and services, with an increasing focus on energy transition and the decarbonization of industrial processes. The Group’s energy activities are developed through dedicated companies, including Duferco Energia S.p.A., active in electricity generation from renewable sources, energy and gas trading, energy efficiency services, and sustainable mobility infrastructures, and Duferco Engineering S.p.A., which operates as an engineering company focused on the development of energy and industrial projects.

The Group’s strategy in the hydrogen sector is consistent with the objectives of energy transition and industrial decarbonization. Duferco aims to integrate green hydrogen into its electricity generation processes, promote local production chains in Sicily, and foster industrial and mobility applications. The investment plan for the Giammoro site in Sicily outlines the vision for the development of a Hydrogen Valley capable of producing green hydrogen through photovoltaic-powered electrolysis, with potential applications in the automotive sector, heavy-duty road transport, and local logistical support.

This strategy is embedded in a context of strong European regulatory drivers (RePowerEU, IPCEI, PNRR) promoting the deployment of hydrogen infrastructures and the substitution of fossil fuels in energy-intensive processes.

2.1.2. De Nora

De Nora is a global leader in electrochemical technologies and operates across a broad range of industrial sectors, including water treatment, chlor-alkali processes, and the hydrogen economy. With more than a century of expertise in electrode manufacturing, the company plays a central role in enabling high-performance electrochemical systems and supporting the industrial transition toward more sustainable energy solutions.

De Nora’s hydrogen strategy is built on a clear and balanced dual-market approach. On one side, the company focuses on large-scale hydrogen plants, where it leverages its long-established leadership in high-efficiency electrodes. These electrodes remain the core technological asset of the company and are essential for utility-scale electrolyzers that require high durability, reliability, and optimized performance. This positioning allows De Nora to contribute to the development of gigawatt-level hydrogen infrastructures and to support strategic global initiatives aimed at scaling up green hydrogen production.

At the same time, De Nora addresses the rapidly growing demand for small and mid-scale, decentralized hydrogen production. In this segment, the company offers dedicated solutions tailored for on-site generation, among which the Dragonfly® System plays a key strategic role. While representing a different market segment from large industrial installations, Dragonfly® strengthens De Nora's ability to serve emerging distributed energy ecosystems, local industrial users, and hydrogen mobility applications.

2.1.3. Power Evolution

Power Evolution is an energy technologies company, founded in 2010, that focuses on the design and production of innovative products and processes with high technological value in the energy sector, and in particular on the development of technologies for renewable energy and for energy efficiency. The company designs and develops systems for energy saving and efficiency, SCADA systems to monitor and provide supervisory control of plants for energy production. The company also carries out research activities in the field of materials and innovative technologies in collaboration with Universities and research centers. The latest R&D project called ATRE, thermal storage for residential application, led to development of a pilot with excellent performance.

Power Evolution's long-term strategy is to build strong references in industrial applications for the hydrogen market.

2.1.4. SNAM

Snam is one of Europe's leading energy infrastructure operators, playing a central role in the development and management of natural gas transportation, storage and regasification networks. In recent years, the company has embarked on a structured industrial and technological transformation pathway aimed at decarbonisation, with the objective of contributing concretely to European climate targets and to the development of a more sustainable, resilient and integrated energy system.

Snam has consistently demonstrated a strong commitment to driving the energy integration by embracing and investing in innovative technologies and new energy vectors. The company firmly believes that these elements are fundamental to building a more secure, sustainable and low-carbon energy future and continues to play a proactive role in shaping the evolution of the energy landscape through research, development, and strategic implementation of cutting-edge solutions. In this context, research, development and innovation activities play a pivotal role. Snam actively participates in European projects and collaborative initiatives that foster the advancement of technological solutions supporting decarbonisation. Among the relevant public projects are MemLab, H2SHIFT, IdrogeMo and HAAS, which represent concrete examples of the company's commitment to advancing innovative technologies for a low-carbon energy system.

MemLab contributes to the study and testing of innovative membrane-based technologies for gas separation and treatment, with the aim of improving process efficiency and facilitating the integration of renewable gases into existing infrastructures. The project is embedded in the broader effort to enhance upgrading and purification solutions, which are key to ensuring the quality, safety and sustainability of energy flows.

H2SHIFT ("Services for Hydrogen Innovation Facilitation and Testing") is a Horizon Europe–funded project that aims to create an Open Innovation Test Bed (OITB) for hydrogen production technologies. Its core mission is to help startups and SMEs move hydrogen technologies from early lab validation to industrial demonstration by giving access to shared test facilities, engineering services, and business support through a Single Entry Point (SEP).

The Hydrogen Valley IdrogeMo project aims to produce hydrogen through water electrolysis using electricity generated from renewable sources. The plant will be equipped with a PEM (Proton Exchange Membrane) electrolyser, powered by a photovoltaic field and a BESS (Battery Energy Storage System). The hydrogen produced will be used to supply local public transport, with potential additional applications in the industrial sector. The project also includes a hydrogen compression system for loading onto high-pressure trailers, ensuring efficient distribution across the territory. Through applied research and demonstration activities at relevant scale, the project supports the definition of technical standards and operational models that enable the safe and efficient evolution of the gas system towards low-emission configurations.

HAAS is an initiative that introduces a leasing business model designed to help industrial companies adopt green hydrogen more easily. Instead of requiring a large upfront investment in electrolyzers, Snam leases containerized electrolysis systems to industrial customers. End users (e.g., an industrial plant) operate the system on-site to produce hydrogen. The model helps "de-risk" hydrogen adoption by allowing companies to test and validate hydrogen use without major capital expenditures.

Taken together, these initiatives demonstrate Snam's commitment to combining industrial solidity with technological innovation, leveraging collaboration with industrial partners, institutions and research centres at European level. For Snam, decarbonisation is not only an environmental challenge, but also a strategic opportunity to rethink the role of energy infrastructures as enablers of the transition, contributing to security of supply, industrial competitiveness and the creation of sustainable value for territories and communities.

In the framework of Hy2Market project and in particular of the Work Package 2, SNAM will provide guidelines to repurpose and share the business case to different infrastructures already existing in Sicily region, and in industries like petrochemicals and refineries.

SNAM will contribute to providing market update in relation to hydrogen production and utilization on the different industrial environments: hydrogen/natural gas turbine, refinery and petrochemicals.

2.1.5. CNR-ITAE

CNR-ITAE (National Research Council – Institute for Advanced Energy Technologies) is one of Italy's most prominent research centers in hydrogen and fuel-cell technologies, contributing significantly to the national and European hydrogen strategies. It is a full member of the Fuel Cells and Hydrogen Joint Technology Initiative and participates in several international hydrogen-focused research programs. Its work spans hydrogen production (including electrolysis), storage, catalysis, hydrogen-based fuels, and system integration with renewable energy sources. The institute plays a central role in supporting the development of green hydrogen infrastructure and is recognized for its contributions to sustainable hydrogen technologies, aligned with Italy's and Europe's decarbonization agendas.

CNR-ITAE plays a central scientific and technical role within the Hy2Market Sicilian pilot. As the research partner of the consortium, CNR-ITAE contributes expertise in system integration, process optimization, and demonstration of hydrogen technologies, acting as coordinator of the Sicilian pilot. Its activities include the development of detailed modelling and simulation of hydrogen–natural gas combustion, the techno-economic optimization of the full energy conversion chain, and scientific support to design and operational decisions. Through advanced computational studies carried out with COMSOL Multiphysics, CNR-ITAE evaluated turbine behavior under hydrogen blending conditions, confirming reductions in NO_x, CO, and CO_2 emissions and validating the environmental benefits of the pilot configuration. Overall, CNR-ITAE ensures the scientific robustness of the project and provides key insights enabling future scale-up and replication in other industrial contexts.

2.2. Peaker Power Plant as Hy2Market Sicily Pilot

The industrial area of Giammoro in Sicily, managed by the Duferco, constitutes an important industrial site for the Sicilian economy, that includes:

- Internal railway, connected to the national rail network
- Direct access to the Duferco Terminal Mediterraneo (DTM), the first private multipurpose container terminal in Sicily
- 5 MWp roof-mounted PV plant (further expansion of approx. 4.5 MWp)
- A 58 MW peaker turbogas plant for electricity production
- An emerging hydrogen valley

Figure 1 View of the Duferco industrial area

The Duferco Peaker Power Plant is a grid-balancing power station (peaker) located in the industrial area of Giammoro – Pace del Mela (ME), Sicily. The plant has a peak capacity of approximately 58 MW and is based on an open-cycle gas turbine fuelled by natural gas, designed to provide dispatchable reserve to the Italian power system upon request of the transmission system operator Terna S.p.A.

The primary objective of this type of power plant is not continuous electricity production, but rather the mitigation of imbalances between electricity supply and demand, particularly in contexts characterized by a high penetration of intermittent renewable energy sources such as wind and photovoltaic power. The technical specifications of the turbine and the open-cycle configuration allow for fast start-up times, high operational flexibility, and a dynamic response to TSO requirements.

The plant was developed as part of the reconversion plan of the Giammoro industrial area, with an initial investment estimated at approximately EUR 30 million, and it obtained the necessary environmental and construction permits in the years preceding its commissioning.

Figure 2 58 MW Duferco Peaker Power Plant

The Peaker Power Plant operates upon dispatch instructions from Terna and not according to a production profile scheduled by the plant operator. Within this framework, Duferco Sviluppo S.p.A. acts as the technical and structural plant operator, while production timing and output levels are determined by the needs of the national electricity system through the TSO.

In terms of participation in the electricity market, the Peaker plant mainly operates within dispatching services, capacity reserve, and grid balancing mechanisms, which are specialized segments of energy system regulation (such as the Dispatching Services Market and ancillary services for Terna).

The following figure shows a typical working profile of the peaker along the entire year.

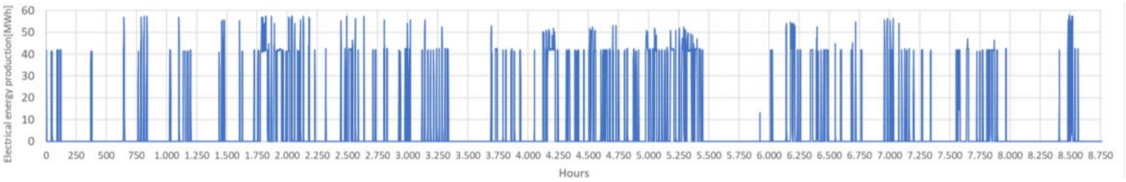
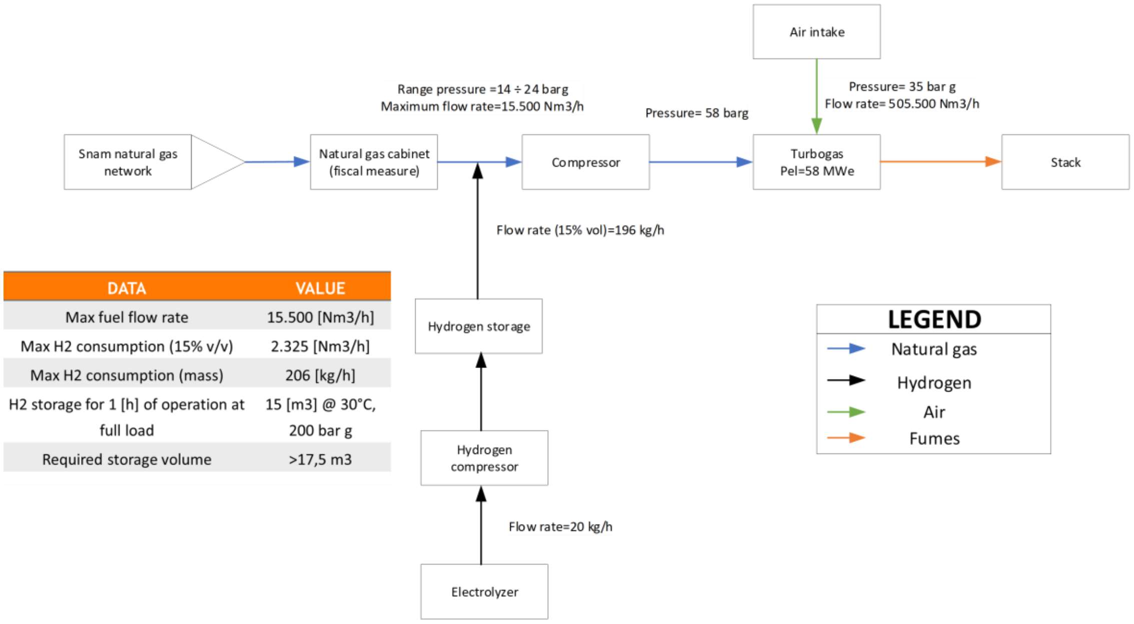


Figure 3 DUFERCO typical peaker working profile

The intrinsic nature of this type of asset qualifies it as a peak capacity reserve rather than as a continuous generation source. The inclusion of this plant in Duferco's asset portfolio contributes to the stability of the Sicilian power grid, which is characterized by a high share of renewable generation and a corresponding need for balancing resources.

The transition from a natural gas peaker turbine to a natural gas/hydrogen blend requires different industrial components to be installed and integrated in a unique plant.

In the following diagram it is reported the preliminary plant diagram which illustrates the integrated energy system under development within the Hy2Market Sicilian pilot, showing how hydrogen is produced, stored, and blended with natural gas before being used in a large gas turbine. Overall, the figure captures the full chain of the pilot system: hydrogen production, compression, storage, blending with natural gas, and final utilization in a large-scale industrial gas turbine. It also highlights the main operating parameters, i.e. pressures, flow rates, and consumption values, illustrating how the system components interface. The process begins with natural gas supplied by the SNAM network. The gas first passes through a fiscal metering cabinet and then enters a compressor, where it is brought to a pressure of 58 bar to meet the requirements of the downstream turbogas unit. The maximum natural gas flow rate handled in this section is 15,500 Nm³/h.



DATA	VALUE
Max fuel flow rate	15.500 [Nm3/h]
Max H2 consumption (15% v/v)	2.325 [Nm3/h]
Max H2 consumption (mass)	206 [kg/h]
H2 storage for 1 [h] of operation at full load	15 [m3] @ 30°C, 200 bar g
Required storage volume	>17,5 m3

Figure 4 Hy2Market Sicilian pilot diagram

In parallel, hydrogen is generated by a 1 MW electrolyzer produced by De Nora. The electrolyzer delivers hydrogen at a flow rate of around 20 kg/h. This hydrogen is then directed to a dedicated compression system that increases its pressure to allow storage in high-pressure tanks, which operate at approximately 200 bar. The storage system is dimensioned to contain enough hydrogen for one hour of operation of the turbine at full load when using a 15% hydrogen–natural gas blend. This corresponds to about 15 m³ of hydrogen at 30°C and a required storage volume exceeding 17.5 m³. At 15% hydrogen by volume, the turbine consumes roughly 2,325 Nm³/h of hydrogen, equivalent to 206 kg/h.

From the storage tanks, compressed hydrogen is metered and fed into the natural gas line, where it is blended before entering the main compressor. The resulting mixture, containing up to 15% hydrogen by volume, is sent to the 58 MW gas turbine, which operates as a peaking unit in the Italian power system. The turbine receives both the fuel blend at 58 bar and the required combustion air through a dedicated intake. The exhaust gases are then released through the stack.

Based on the preliminary design, the plant will consist of the following main components:

- Water supply system, which provides the feedwater to the electrolyzer, enabling the electrolysis process that splits water into hydrogen and oxygen.
- 1 MW electrolyzer, complete with a reverse-osmosis water purification unit, cooling systems, and a hydrogen purification module at the outlet.
- 1.6 m³ buffer tank, used for storing hydrogen at 35 barg at the electrolyzer outlet.
- Hydrogen compressor, designed to increase the pressure from 30–35 barg up to 200 barg.

- High-pressure hydrogen storage, consisting of six cylinders of 2,335 liters each (total 14,010 liters), operating at 200 barg (202.879 kg of H_2).
- Instrument air distribution system.
- Nitrogen storage and distribution system for purging operations, supplied either from a cylinder pack or a nitrogen generator.
- Auxiliary service systems for electrical distribution, waste water disposal, drainage, and related utilities.

The full design of the hydrogen production, storage and blending is close to the end, including the related permitting activities. Details on the design activity are reported in the following section.

3. Design of the plant for hydrogen production, storage and blending with natural gas

Topics covered in this chapter:

- Permitting activities to enable pilot construction and operation
- Design of the Sicily pilot
- Architecture and functionality
- Structures and engineering works
- Hydrology and hydraulics
- Electrical layout

3.1. Permitting Activities within the Sicilian Pilot

Within the Hy2Market project, Duferco plays a central role as the industrial host of the pilot at the Giammoro site. Furthermore, it is responsible for the technical, permitting, and design coordination of the infrastructures required for the integration of hydrogen into the Peaker Power Plant and for the realization of the green hydrogen production facility. The activities directly managed by Duferco are structured across several operational areas, which are currently at an advanced stage of development.

Duferco is responsible for managing and coordinating the permitting processes, which represent a key determinant for the technical feasibility and project timeline. Power Evolution coordinates Task T2.2 - Site Management and Scale-up. In this context, it is responsible for the design and installation of the pilot plant for the production of green hydrogen, with a capacity of 1 MW, at the Duferco site in Giammoro.

The Hy2Market project includes two distinct yet interconnected interventions: the supply of the existing Peaker plant with a CH_4–H_2 blend, including the necessary auxiliary works (hydrogen supply line, blending station, and control systems), and the construction of a new green hydrogen production plant in an area adjacent to the existing site.

With reference to the Peaker plant, which was already excluded from the Environmental Impact Assessment (EIA, or "Valutazione di Impatto Ambientale", VIA) procedure during its original authorization phase, the introduction of the methane–hydrogen blend and the related auxiliary works constitute a plant modification. A preliminary assessment pursuant to Article 6, paragraph 9, of Legislative Decree 152/2006 is therefore ongoing, with the objective of demonstrating and confirming the non-relevance of the proposed modification for EIA purposes. Duferco is finalizing the collection and organization of the technical and environmental information required to support this assessment and to enable the competent authorities to issue a reasoned formal opinion on the non-subjection of the modification to further EIA procedures.

As regards the green hydrogen production plant, at present it does not qualify as an "integrated chemical installation" subject to national EIA, as the connection with the Peaker plant is infrastructural and energy-related rather than functional, in line with the clarification provided by the Ministry of the Environment and Energy Security (MASE) through Question No. ("Interpello N.") 124801/2023. With respect to the Integrated Environmental Authorization (AIA), Directive (EU) 2024/1785, whose transposition into national legislation is expected by June 2026, establishes that hydrogen production plants based on electrolysis are subject to AIA only if their production capacity exceeds 50 tonnes of hydrogen per day. The plant envisaged within the Hy2Market project has a production capacity well below this threshold and, therefore, will not be subject to AIA once the Directive is transposed. Duferco nevertheless continues to monitor the regulatory framework to ensure full compliance with both current and future requirements.

The H2 plant is included in the list of activities subject to fire prevention checks by the designated fire department.

The H2 plant is subject to a specific risk assessment, which was conducted in accordance with the procedures set out in Annex I of the Ministerial Decree of August 7, 2012.

The plant was designed in accordance with the requirements contained in Chapter V.2 of the Ministerial Decree of August 3, 2015, and the technical rules for fire prevention and related fire safety measures of the Ministerial Decree of July 7, 2023, and the Ministerial Decree of October 23, 2018.

Furthermore, as hydrogen is a highly flammable and explosive gas, compliance with the ATEX (ATmosphères EXplosibles) Directive 2014/34/EU, which regulates the essential safety requirements for equipment and systems intended for use in potentially explosive atmospheres, is essential. All phases of the project, from design to commissioning, must ensure compliance with this legislation through the assessment and classification of explosion risk areas, the selection of ATEX-compliant equipment, and the adoption of preventive measures for risk management.

In addition, in order to proceed with the construction of the plant, it is necessary to obtain the administrative authorizations required by national and regional regulations:

- **SCIA (Certified Notice of Commencement of Work)**: for works and installations that do not require prior authorization but must be communicated to the competent authority before work begins.
- **AIA (Integrated Environmental Authorization)**: for plants subject to significant potential environmental impacts, ensuring compliance with emission limits and environmental conditions. Only a non-substantial modification of the current authorization is needed

The new European directive (2024/1785 DIRECTIVE (EU) 2024/1785 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 April 2024) not yet transposed by the member states, sets the daily hydrogen production at 50 tonnes H_2/day, for which the plant must be subject to AIA. Compliance with these procedures ensures that the plant complies with safety, environmental protection, and land-use planning regulations, thus ensuring the full legitimacy of the production activity.

Some of the most important regulations are listed below.

- Ministerial Decree of July 7, 2023 "Technical fire prevention regulation for the identification of risk analysis methodologies and fire safety measures to be adopted for the design, construction, and operation of hydrogen production plants using electrolysis and related storage systems."
- Ministerial Decree of October 23, 2018: "Technical fire prevention regulations for the design, construction, and operation of hydrogen distribution systems for motor vehicles."
- Ministerial Decree of August 7, 2012: "Provisions relating to the procedures for submitting applications concerning fire prevention procedures and the documentation to be attached."
- Ministerial Decree of August 3, 2015, "Approval of technical standards for fire prevention."
- J2601/2_202307
- ISO 14687:2019
- UNI ISO 19880-1:2020
- ISO 11114-4 “Transportable gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 4: Test methods for selecting steels resistant to hydrogen embrittlement.”
- CNR UNI 10011 “Steel structures.”
- DIN 19704 “Hydraulic steel structures - Calculation criteria.”
- DIN 19705 “Hydraulic steel structures - Recommendations for design, construction, and assembly.”

- DPR 459 “Machinery Directive.”
- UNI 1285–68 “Pipe thickness calculation.”
- CEI EN 60529 “Degrees of protection provided by enclosures.”
- CEI 17–5 “Low voltage equipment.”
- CEI 17–50 “Low-voltage equipment Part 4: Contactors.”
- CEI 17–50 “Low-voltage equipment Part 5: Control circuit devices and switching elements.”
- CEI/210 “Electromagnetic compatibility – Generic standard on emissions Part 2: Industrial environment.”
- IEC/210 “Electromagnetic compatibility – Generic standard for immunity Part 2: Industrial environment.”
- IEC EN 61131-3 “Programmable controllers Part 3: Programming languages.”
- IEC 3-35 “Preparation of functional diagrams for control systems.”
- CEI 11–1 “Electrical installations with voltage greater than 1 kV in AC.”
- CEI 17–13 “Assembled low voltage protection and control equipment (LV switchboards).”
- CEI 20-20 “Polyvinyl chloride insulated cables with rated voltage ≤ 450/750 V.”
- CEI 20–22 “Fire tests on electrical cables.”
- CEI 20–27 “Power and signaling cables: designation system.”
- CEI 20–40 “Guide for the use of low voltage cables.”
- CEI 11–20 “Energy production systems and uninterruptible power supplies connected to category I and II networks.”
- CEI 64-8 “Electrical installations with a rated voltage not exceeding 1000 V AC and 1500 V DC.”
- EN 60529 “Degrees of protection provided by enclosures (IP code).”
- EEC Directive 89/336 (“Electromagnetic Compatibility”)
- CEI EN 50081-2 standards
- CEI EN 50082-2 (“Industrial environments”)
- EEC Directives 73/23 and 93/68 (“Low Voltage”)
- CEI 17-6 (IEC 298)
- CEI 17-21 (IEC 694)
- CEI 17-1 (IEC 56)

Below is an overview of which of the main European hydrogen directives and policies have been implemented in Italy, together with the main Italian regulation specifically for Hydrogen.

<table>
<tr><th colspan="3">Implementation of European regulations</th></tr>
<tr><th>MEASURE</th><th></th><th>DISCIPLINE</th></tr>
<tr><td>RED II</td><td>D.lgs. 199/2021
Art. 38 e 46</td><td>Definition of authorization processes for hydrogen plants</td></tr>
<tr><td>AFID</td><td>D.lgs. 257/2016</td><td>Development plan for H2 refueling stations</td></tr>
</table>

	SAFETY	
Hydrogen Production Plants Regulation	D.M. 07/07/2023	Provisions on the design, construction, and operation for fire prevention purposes of H2 production plants through electrolysis and storage facilities
	INCENTIVES AND SIMPLIFICATIONS	
DL PNRR bis	DL 36/2022 Art. 23	Provisions regarding the production and consumption of hydrogen from renewable sources, the granting of water withdrawals for irrigation use, and the acceleration of approval procedures for basin plans (exemption from system charges)
DL Aiuti bis	DL 115/2022 Art. 32 e 33	Authorization procedures for areas of national strategic interest (including hydrogen)
DM Incentivi idrogeno verde	DM 21/09/2022	Conditions for access to incentives on renewable energy consumption in electrolysis plants for the production of green hydrogen.
DL Semplificazioni PNRR	DL 13/2023	Hydrogen authorization simplifications

Table 1 Summary of main European regulations on hydrogen.

The permitting scope also includes fire prevention and fire safety aspects, in accordance with the applicable legislation, and with the Decree of 7 July 2023. The fire prevention design has been completed by the design specialist and submitted to the competent Fire Brigade Authority ("Vigili del Fuoco"); a formal opinion is currently pending. The development of the fire safety design has enabled the definition of a final plant layout, optimized in terms of safety criteria, safety distances, and functional organization of the different plant sections.

Specific studies have been developed to respect the limitations in terms of safety internal and external distances (Figure 5).

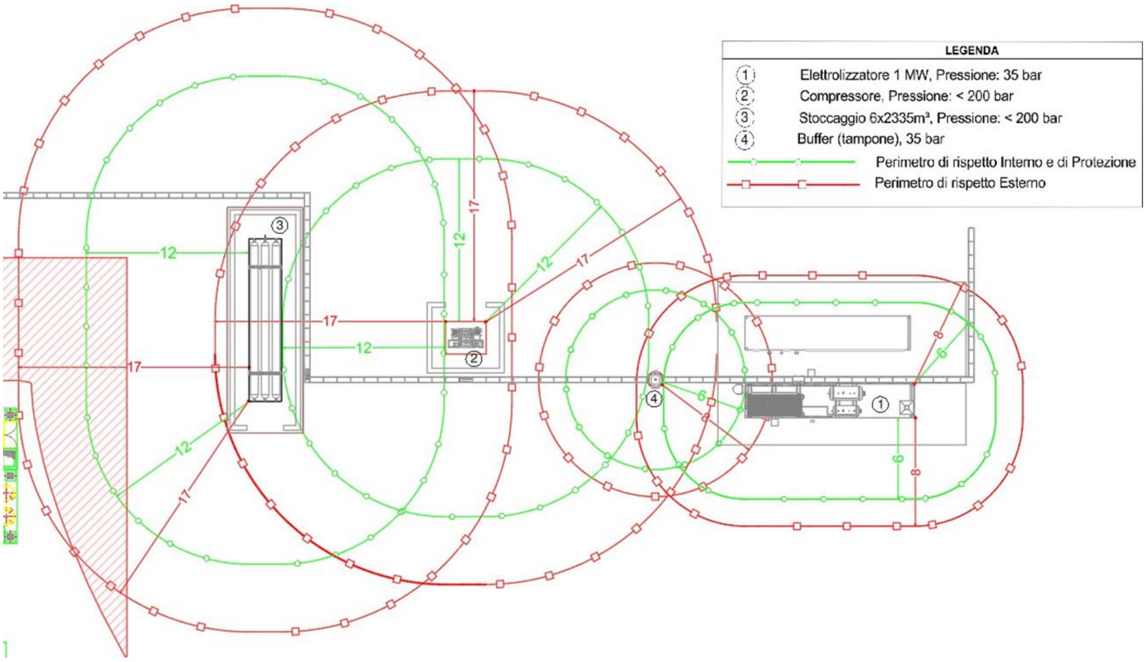


Figure 5 Study of internal and external safety distances in accordance with Ministerial Decree of July 7, 2023

As an example, the following figure shows one of the technical drawings submitted to the local fire department, representing the whole plant layout with a representation of the calculated safety distances.

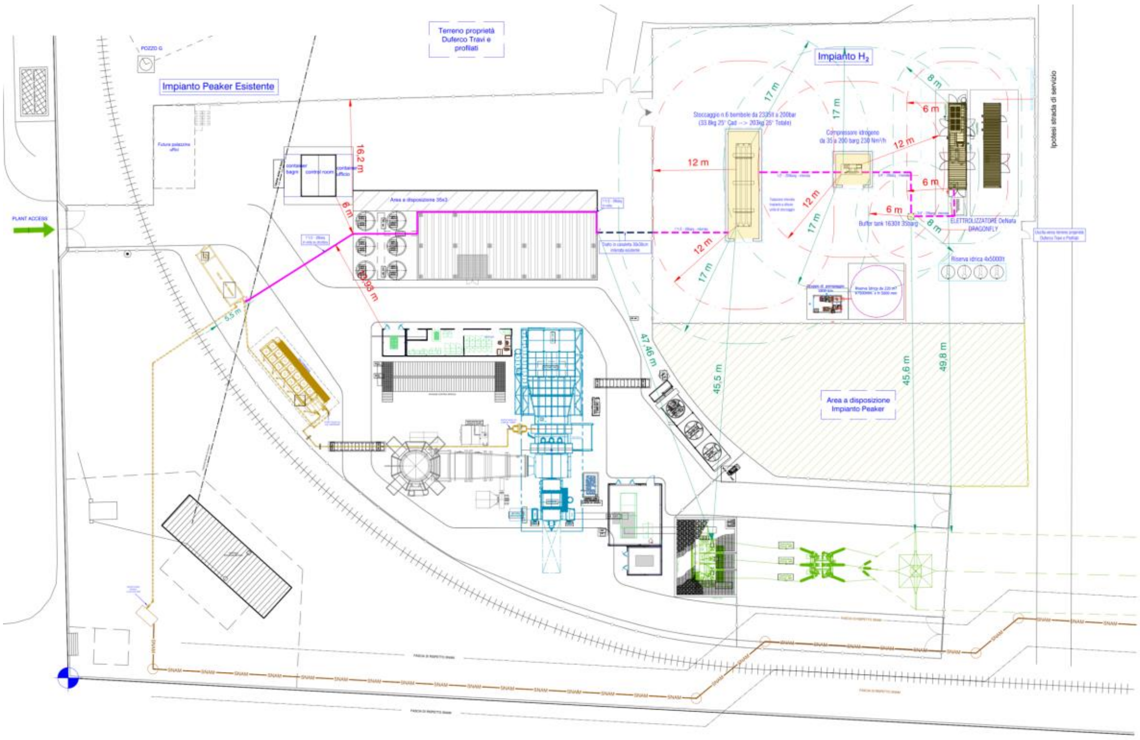


Figure 6 Safety distances in the hydrogen plant layout

Duferco is also responsible for the design and coordination of the civil works (OOCC) associated with the Hy2Market project. The detailed design of the civil works has been completed, including the foundations for the various components of the hydrogen production plant and the auxiliary works related to the Peaker plant, as well as the prefabricated trench intended for medium- and low-voltage electrical distribution. In parallel, the bill of quantities and cost estimate has been prepared, forming the basis for the procurement process of the contractor responsible for the execution of the civil works.

At present, the documentation required for the deposit of the structural designs with the Genio Civile of Messina is under preparation, in compliance with national and regional regulations on structural works and seismic safety. Following the deposit, the Certified Notice of Commencement of Activities (SCIA) will be submitted to initiate construction activities on site. Duferco will retain responsibility for coordinating the construction supervision of the structural works, ensuring proper execution in accordance with the approved designs, permitting conditions, and applicable safety and quality requirements.

3.2. Design of the Sicilian Hydrogen Pilot

The area involved in the project is located adjacent to Duferco's peaker turbine power plant within the industrial site of Giammoro (Sicily).

Figure 7 Aerial view of the area involved in the project

3.2.1. Site Characteristics

- Area: Giammoro (Messina)
- GPS coordinates: 38° 01' 4.3" N 15° 17' 53.7" E
- (38.0178611° N – 15.29825° E)
- Altitude: 12 m above sea level
- Seismic Zone: Zone 2 (Uniform Building Code)
- Minimum air temperature: 9 °C
- Maximum air temperature: 30 °C
- Average air temperature: 19 °C
- Maximum relative humidity: 100%
- Average relative humidity: 60%
- Minimum atmospheric pressure: 993 mbarg
- Maximum atmospheric pressure: 1013 mbarg
- Rainfall intensity: 7.2 mm/h

The area where the plant will be built is in the Giammoro industrial zone in the municipality of Pace del Mela (ME).

It is located in the wide alluvial plain that stretches from the foothills of the Peloritani Mountains to the sea and which, in this area, reaches a considerable size due to the contributions of the Floripotema (or Corriolo) and Niceto streams.

Both of these streams have a large catchment area and are quite long.

The site is already characterized by a small industrial production cluster. Based on the environmental and territorial analysis carried out, the intervention is compatible with the geotechnical and geological components that characterize the area, as:

- No increase in the impermeable surface area is expected compared to the existing one;
- The excavations planned are very limited in size.
- The area is not characterized by elements that could pose a risk of landslides or avalanches;
- The site is at a safe distance from the Floripotema and Niceto streams.

With regard to basic seismic hazard, with reference to the seismic hazard map of the national territory (O.P.C.M., 28/04/2006 no. 3519), the maximum soil acceleration range with a probable excess of 10% in 50 years referring to rigid soils is between 0.150 g and 0.175 g in the study area (Stucchi M., 2004).

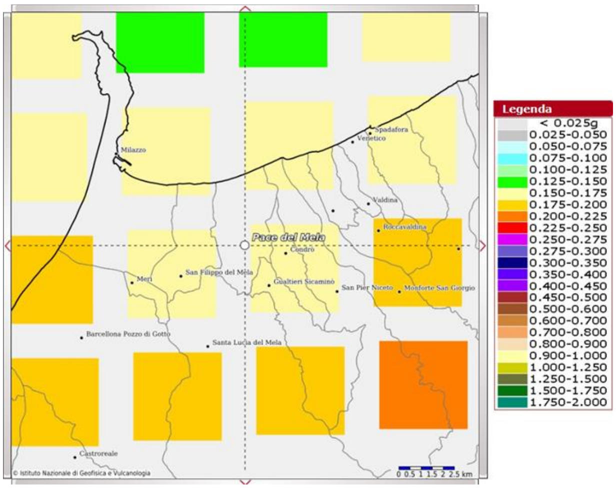


Figure 8 Map of seismic hazard in the area

The area is classified as seismic category 2 medium risk **(DGR Sicily no. 408/2003)**. All structures will be designed in compliance with the Technical Standards for Construction (NTC 2018), with particular reference to seismic actions.

- **Use class II**
- **Nominal life: 50 years**

The plant is located in an existing industrial area, within the grounds of the Duferdofin factory, which is already urbanized and equipped with the necessary infrastructure. There are no landscape, environmental, or hydrogeological constraints.

There is no archaeological evidence in the area of intervention according to the preliminary verification pursuant to Articles 95 and 96 of the Public Contracts Code. Therefore, no further archaeological investigation is necessary.

3.2.2. Systems and Safety

The plant is designed in full compliance with current safety regulations, in particular:

- **ATEX Directive** (2014/34/EU and 99/92/EC), for the prevention of risks related to potentially explosive atmospheres, through:
    - Classification of risk areas (Zones 1 and 2);
    - Exclusive use of ATEX-certified equipment and components in the relevant sectors;
    - Implementation of intrinsically safe electrical and control systems;
    - Adoption of minimum internal and external safety distances, in accordance with regulations and best technical practices.
- **PED Directive** (2014/68/EU) on pressure equipment, applied to all components subject to pressure (compressors, tanks, pipes), with verification of design, manufacturing, testing, and certification requirements.
- **ISO 22734 standard**, which establishes safety and performance requirements for electrolysers intended for the production of hydrogen by water electrolysis.

The plant will also be equipped with a comprehensive protection, monitoring, and emergency management system, including:

- H_2 gas detectors for the timely detection of any leaks, positioned at strategic points (electrolyzer, compressor, storage);
- Visual/acoustic alarm systems connected to the automation system;
- Forced and natural ventilation for the dilution of hydrogen in closed environments and the prevention of accumulation;
- Emergency interlock systems activated mechanically or via SCADA automation, for controlled shutdown of the plant in the event of a failure or critical alarm;
- Safety valves and controlled discharge on all high-pressure lines;
- Blast panels and passive barriers for protection against accidental overpressure;
- Grounding system and protection against electrostatic discharge.

The safety plan also includes:

- A **preventive and corrective maintenance program**, in accordance with manufacturers' specifications and current regulations;
- **Specific training for personnel** on the safe management of hydrogen systems, including response to emergency situations;

Drafting of an **Internal Emergency Plan** (IEP) and coordination with local authorities for external safety (fire department, civil protection, ARPA, etc.).

3.2.3. Plant Layout

The lots involved in the project are flat and suitable for accommodating all the elements of the plant. The yards will be arranged with appropriate slopes to direct rainwater towards the drainage system. The internal routes (pipes, cable ducts) will follow a linear and rational pattern, integrating with the existing structures in the Peaker power plant. All internal pipes will be laid underground at a depth of 1.2-1.5 meters, with slopes leading to drainage collection tanks. The tunnel that will house the pipes will be located above ground in the yard to minimize the entry of water and dust. The layout of the plant has been designed to optimize operational functionality (Figure 9-12):

- Clear separation between water treatment, hydrogen production, and compression/storage areas
- Safety distances between the electrolyzer and hydrogen tanks (>8 meters)
- Maneuvering areas for maintenance vehicles

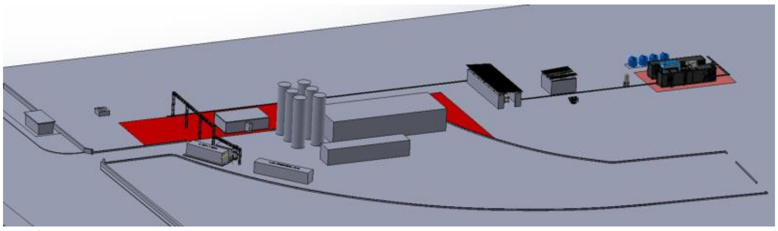


Figure 9 3D CAD View of the system

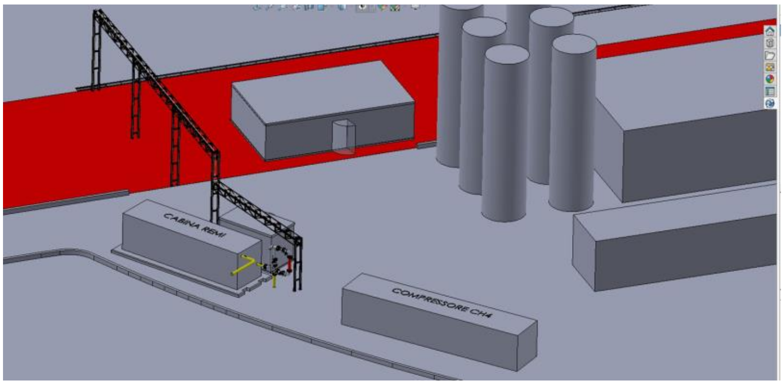


Figure 10 3D CAD View of the control cabin of the pipe bridge and hydrogen mixer near the REMI cabin

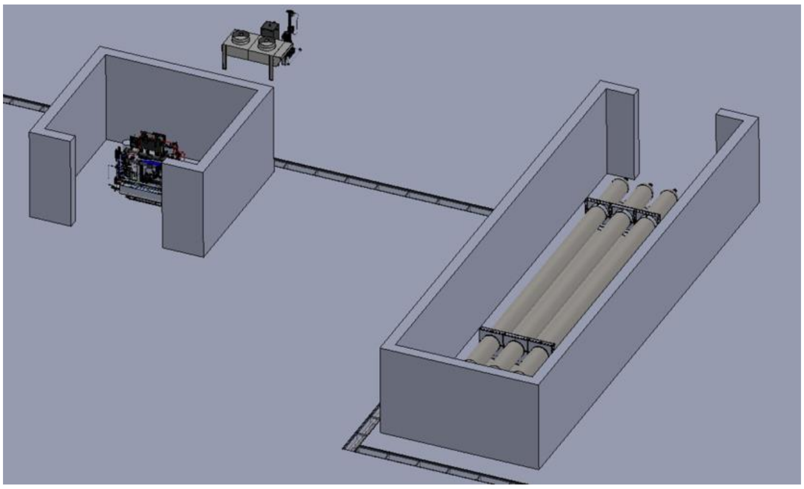


Figure 11 3D CAD View of the bunkers housing the hydrogen compressor and storage cylinders

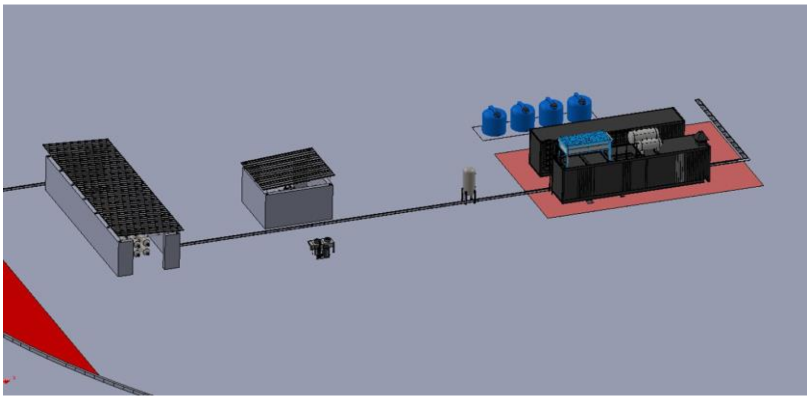


Figure 12 3D CAD View of the electrolyzer area on the right and hydrogen bunker and cylinders on the left.

The plant consists of prefabricated modules (electrolyzer, compressor, storage system) arranged according to criteria of functional efficiency and safety, with adequate internal roads for access by service and maintenance vehicles as well as any emergency vehicles.

3.2.4. Structures and Engineering Works

Duferco, as responsible for the engineering and coordination of the civil works (OOCC), together Power Evolution, as responsible of the overall design, finalized the detailed design phase, covering the foundations for all components of the hydrogen production facility, the auxiliary structures related to the Peaker plant, and the prefabricated trench system intended for medium- and low-voltage electrical distribution. The load-bearing structures are reinforced concrete slabs. The walls forming the safety bunkers will also be made of reinforced concrete. Prefabricated concrete or metal structures are planned for the transformer and distribution cabins. Light metal structures are planned to cover the main hydrogen tanks and the compressor bunker. These covers are optional and are not mandatory for the safety of the site or the integrity of the components they would cover. Both the storage cylinders and the hydrogen compressor are suitable for outdoor use. The hydrogen production control room will be located in an existing building.

The technical containers are installed on reinforced concrete bases, designed to support permanent and accidental loads in accordance with regulations.

The walls of the protective bunkers for the tanks and the hydrogen compressor will be dimensioned to withstand any explosions and divert the energy upwards where there will be no cover or, at most, a light cover raised from the wall, allowing any shock wave to escape.

The roof covering the tanks will allow free air circulation and will be designed to prevent the formation of dangerous gas pockets.

Estimating the explosive energy of the hydrogen stored in the tanks at a total of 400 kg, in the event of an explosion, the pressure on the walls of the bunker is estimated to be less than 10 kg/cm².

In the two figures below it is reported as example an overview of the load-bearing structures included in the overall plant layout and a detailed design of the load-bearing structure of the electrolyzer and the buffer tank.

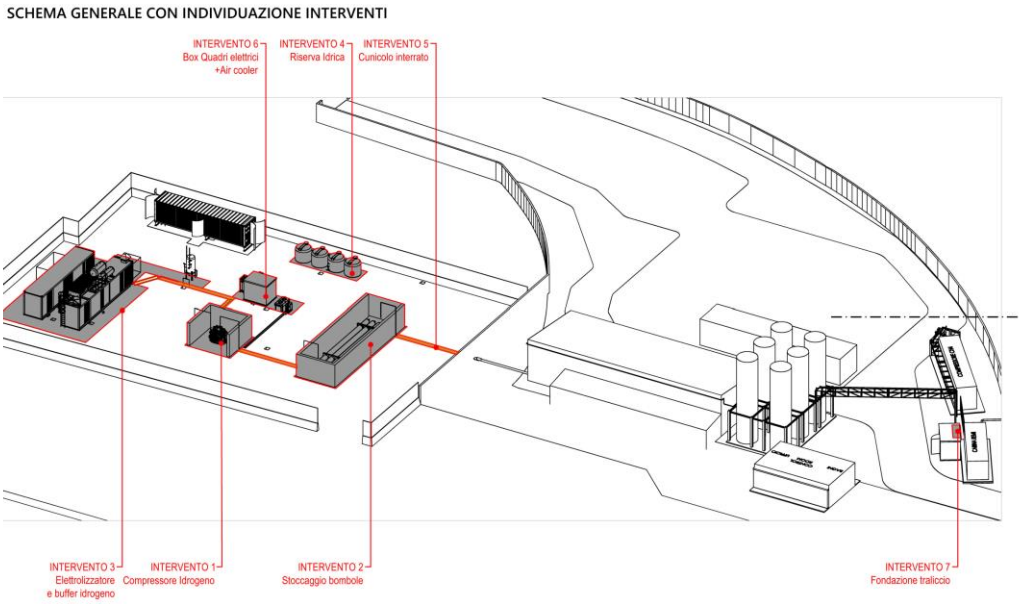


Figure 13 Overview of the load-bearing structures

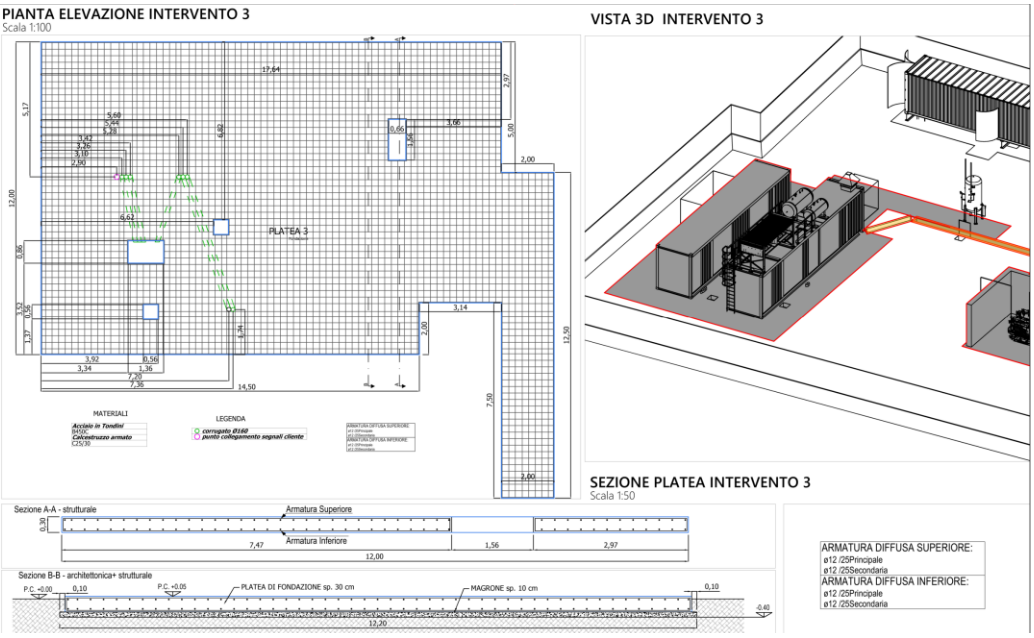


Figure 14 Detailed design of the load-bearing structures of the electrolyzer and the buffer tank

3.2.5. Hydrology and Hydraulics

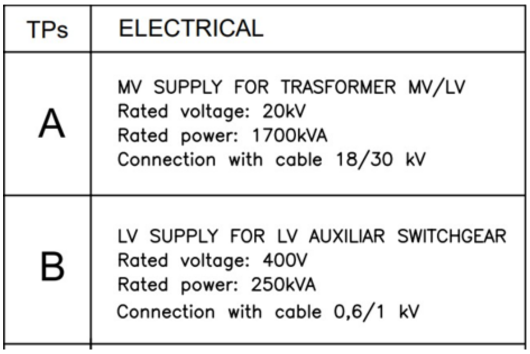
The most significant water discharge comes from the demineralization system, which will discharge a variable flow rate of 200 to 600 liters/hour of concentrated water during hydrogen production, depending on the composition of the water used. This water comes from the concentration of water available in the raw water storage tanks and will contain the same types of pollutants found in raw water but in higher concentrations. Since drinking water will be used, or water with pollutant limits slightly exceeding those established for drinking water, in principle the concentrate will have a composition such that it can follow the same conduits as rainwater.

3.2.6. Electrical Design

Duferco oversees the overall electrical design of the plant, which is a key element for the functional integration of hydrogen production, auxiliary systems, and the Peaker Power Plant. A contractor has already been appointed for both the detailed electrical design and the supply of the main electrical equipment.

Detailed studies are currently ongoing concerning the medium-voltage (MV) grid connection, the configuration of the internal MV and LV distribution network, and the design of the electrical substation, with particular attention to reliability, operational safety, and compatibility with the different operating regimes of the plant.

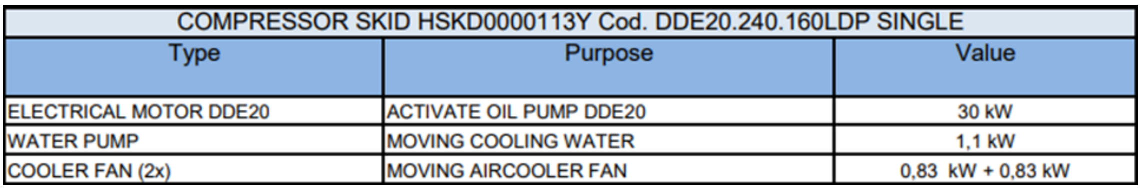
Downstream of the high-voltage electricity supply delivery point, there will be a transformer substation and a distribution panel to supply all the components and systems of the low-voltage H2 plant. A high-voltage line will directly supply the electrolyzer service container. The electrolyzer rectifier is powered by high-voltage at 20,000 volts with a power consumption of 1700 kVA. The electrolyzer's auxiliary equipment must be powered by 400 volts and has a power requirement of 250 kVA.



TPs	ELECTRICAL
A	MV SUPPLY FOR TRASFORMER MV/LV Rated voltage: 20kV Rated power: 1700kVA Connection with cable 18/30 kV
B	LV SUPPLY FOR LV AUXILIAR SWITCHGEAR Rated voltage: 400V Rated power: 250kVA Connection with cable 0,6/1 kV

Table 2 Summary of power supplies De Nora electrolyzer

The hydrogen compressor will also be powered at 400 volts and has an installed power of 30 kW for the compression part and another 2.76 kW for the pumps and fans of the compressor cooling unit.



COMPRESSOR SKID HSKD0000113Y Cod. DDE20.240.160LDP SINGLE		
Type	Purpose	Value
ELECTRICAL MOTOR DDE20	ACTIVATE OIL PUMP DDE20	30 kW
WATER PUMP	MOVING COOLING WATER	1,1 kW
COOLER FAN (2x)	MOVING AIRCOOLER FAN	0,83 kW + 0,83 kW

Table 3 Summary of power supplies for the hydrogen compressor

The electrical distribution network will be constructed ensuring (at the level of switchboards and conduits) sufficient free space (at least 30%) to allow for the installation of other cables/components in the future.

The medium voltage (MV) cables connecting the medium voltage delivery substation to the production plant components will be of a suitable cross-section and laid in corrugated pipes directly buried in the ground, at a suitable depth to be determined during the executive design phase.

The cable route will be as short as possible and parallel to the facade of the buildings, if any. Signal cables will be laid in the trenches for electrical conduits and inside a dedicated rigid pipe of suitable diameter, separated from the power cables.

Line losses will be calculated for each cable and the most advantageous technical and economic solution will be chosen. Finally, in addition to complying with current regulations, the cables will be designed to maximize and optimize the energy transported.

In the figure below it is reported a preliminary electrical schemes of the MV connection, the transformer and the low voltage distribution panel.

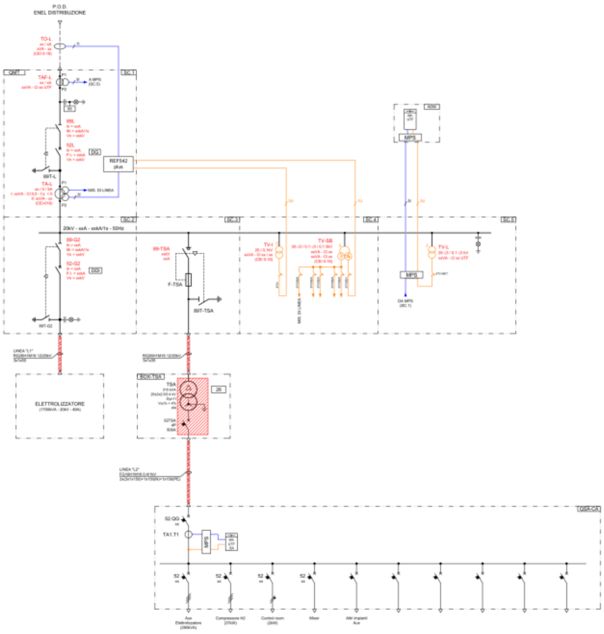


Figure 15 Preliminary single line electrical scheme

The distribution system for the hydrogen production plant will be developed in the most appropriate, correct, and optimal manner, both from a technical and economic point of view, in compliance with current regulations.

The following components will be selected and sized:

- main distribution panels
- power supply for the electrolysis system and auxiliary services
- transformers
- UPS (uninterruptible power supply) systems, and emergency systems.

The design of the grounding system for all equipment within the plant requires special attention in order to prevent dangerous step and contact voltages in the event of a fault. In particular, the grounding system will have the following functions:

- Dispersion of low and medium voltage fault currents.
- Dispersion into the ground of currents conveyed by lightning protection systems.

All equipment and metal masses shall be connected to the grounding system. The grounding network shall be designed and constructed in accordance with the provisions of CEI standards and their subsequent amendments and additions (as amended).

3.2.7. Automation and Control System

The operation of the electrolyzer, the compressor, and the interaction between the various parts of the system and the fill level of the storage tanks will be controlled and monitored by an automation system. The user interface of this system will be located on a touch screen panel and PC.

The control room will be located in the existing building.

A command and control power supply panel must be installed near the plant according to the instructions provided by the plant personnel. The control panel must include a PLC (FAIL SAFE), a redundant 24V power supply with fault indication, equipped with I/O cards suitable for managing the utilities in the project PCIDs.

A 10-12" touchscreen HMI panel must be installed on the front of the panel to manage the system locally. ON/OFF switches, RUN feedback, EMO (with safety function), and alarm indicator lights must also be provided.

The panel must have a spare capacity of at least 30% in the sizing of the AI, AO, DI, DO, terminal blocks, etc. All DOs that directly control electric motor drives, even if small (e.g., small valves), must be equipped with backup relays. The panel will also include a service socket, a lighting socket, and two spare switches (6A).

A light tower and an additional EMO (with safety function) must be installed near the system to allow the operator to perform an emergency stop near the system. Isolators must also be provided on the pump to allow maintenance operations to be carried out.

A dedicated panel must also be created for the pump inverter controls with relative disconnect switches.

Inside the control panel, a network switch must be installed and the relevant ETH Cat6 network cable laid with a communication driver for dialogue between the PLC and the SCADA plant software.

The PLC software must not be password-protected, and the various sections must be commented on, with the relevant name tags.

The control system must be interfaced with the "Siemens WINCC" plant SCADA supervision system.

A SCADA system must be created with all the graphic pages and settings present on the touchscreen, and must allow the operation of all plant components. In addition, logs of all alarms and events (automatic/manual mode switch, operator login on HMI, etc.) must be provided.

4. Process Components

Topics covered in this chapter:

- Permitting activities to enable pilot construction and operation
- Design of the Sicily pilot
- Hydrogen supply chain: process components

In this section, a description and an explanation of the main components of the hydrogen production, storage and blend plant, it is reported. which is composed as following:

- Electrolyzer
- Buffer tank
- Hydrogen compressor
- High-pressure hydrogen storage
- H_2–Natural Gas Mixer

Downstream of the storage system, a dedicated point will be installed along the methane supply line to allow the injection of hydrogen. The hydrogen flow rate will be regulated upstream of a static mixer, which, by inducing high turbulence in the gas streams, ensures proper homogenization of the methane–hydrogen mixture.

4.1. Electrolysis System

The heart of the hydrogen production plant is the electrolyzer. The electrolyzer is provided by De Nora, one of the project partners. The Dragonfly® electrolysis system represents a significant innovation in the field of hydrogen production, featuring a modularized and containerized design that facilitates installation and reduces both construction and operating costs.

The Dragonfly® System is De Nora's containerized alkaline water electrolysis solution engineered to deliver high-performance green hydrogen production with maximum simplicity and reliability. Built upon De Nora's century-long expertise in electrochemistry, the system integrates De Nora's proprietary high-efficiency electrodes, a core differentiating element that improves electrochemical performance and long-term durability.

Designed for operation at high current density, the Dragonfly® System reaches values up to 10–12 kA/m², enabling increased hydrogen output while maintaining robust efficiency. This optimization aims to exploit high level overall system performance and reduced specific power consumption.

A key characteristic of Dragonfly® is its plug-and-play architecture: all required utilities, including power electronics, water treatment, auxiliary and safety systems, are fully integrated within the unit.

In particular, the full package includes:

- Electrolyzer, composed of all pertaining items to allow operability
    - Anodic and Cathodic Electrodes
    - Bipolar Plates
    - Separator/Diaphragm
    - Ancillary Cell Internals (Gaskets)
    - Bulkheads
    - Tightening System (Tie Rods, Nuts, Spring Washers)
    - Electrical Connections
    - Electrical Insulators
    - Process Connections
- Balance of Plant composed of all pertaining items to allow operability, composed of:
    - Transformer Rectifier
    - Process Equipment, with dedicated valves and instrumentation for:
        - Anolyte circulation system
        - Catholyte circulation system
        - Demineralized Water Feed
    - Feed Water Treatment and Demineralized Water Tank to ensure operability with water in line with Table (Annex)
    - Auxiliary Fluids Systems
        - Nitrogen Generation and Storage
        - Compressed Air Generation and Storage
    - MCC/PLC
    - Heat Removal Circuit (comprehensive of air-cooled heat exchanger)

    - All Pertaining Safety Systems:
        - In Process (HTO/OTH)
        - Off Process
            - IR camera
            - Forced Ventilation Unit
            - Uninterrupted Power System to ensure Safety Systems interventions in case of alarm
            - Door Lock with Unit in Operation
    - Secondary system for hydrogen treatment (DeOxO)

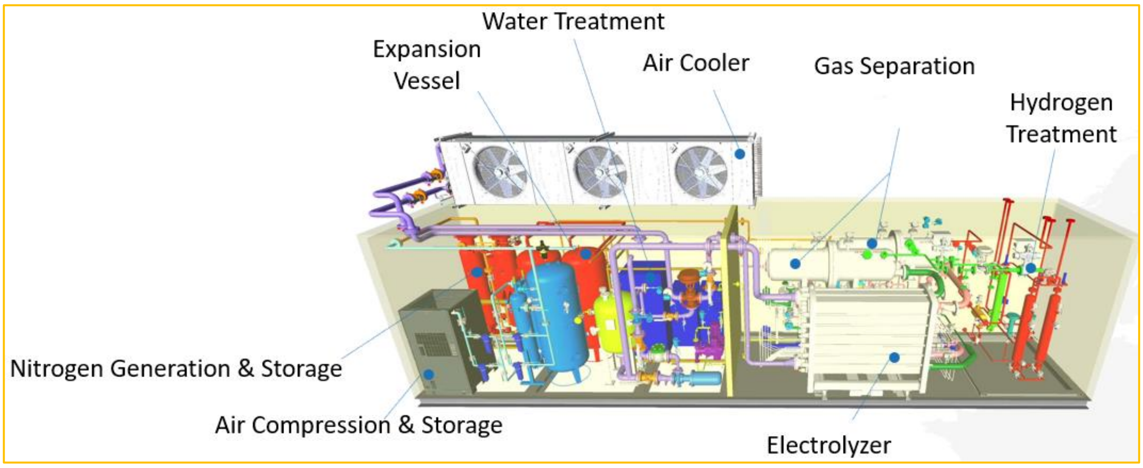


Figure 16 Dragonfly container layout

The entire system is fully containerized, featuring a compact footprint engineered to simplify logistics, reduce civil works, and support decentralized hydrogen production in a wide range of industrial and energy applications. Its pressurized design, operational flexibility, and high responsiveness to load variations further enhance performance in dynamic and renewable-powered environments.

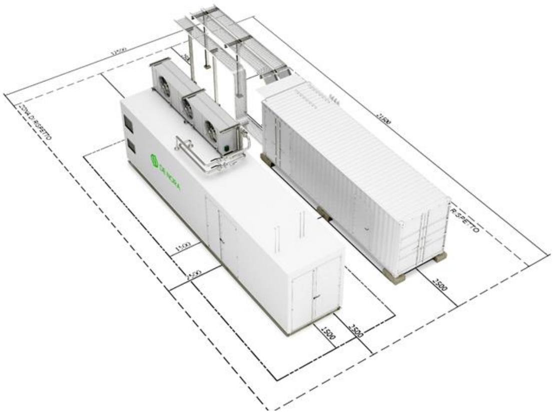


Figure 17 Dragonfly containerized system

Overall, the Dragonfly® System embodies De Nora's commitment to advancing next-generation alkaline water electrolysis by providing a compact, efficient, and robust hydrogen production platform suitable for small- and medium-scale industrial applications.

Figure 18 shows the specific energy consumption per kilogram of hydrogen produced, as a function of the electrolyzer's operating load percentage. When the plant operates at 100% load, the specific consumption reaches a minimum.

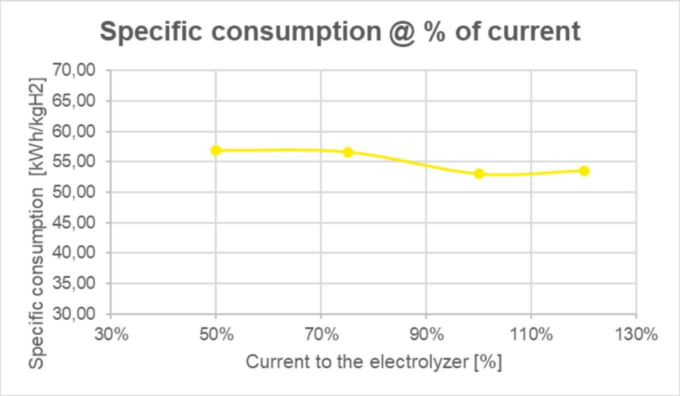


Figure 18 Electrolyzer specific energy consumption

This system uses an electrochemical architecture that includes cells arranged in series with advanced catalytic coatings, ensuring optimized energy consumption and efficient production of hydrogen and oxygen. The hydrogen produced achieves a purity of over 99.999%, while the oxygen exceeds 99.5% purity. The technology used allows for significant reductions in the footprint of the units, as well as maximizing current density and minimizing energy costs. The units are fully pre-engineered and pre-assembled, ready to be connected to existing infrastructure with minimal on-site installation requirements. This plug-and-play feature, combined with remote control and monitoring capabilities, makes the system highly adaptable to various industrial contexts, promoting effective and rapid integration into existing processes. The electrolyzer chosen for the current project is the 1 MW model and has the following characteristics:

- Hydrogen production of 206 Nm^3/h with a consumption of 53.7 kWh/kg
- Electrolyzer design pressure 30 bar
- Max hydrogen outlet pressure 28.2 bar

The electrolyzer uses electricity to split ionized water molecules into their basic elements, generating H_2 from the cathode and O_2 from the anode.

Depending on the intended use of the hydrogen output, the electrolyzer can be equipped with a purifier and dryer that removes traces of moisture from the hydrogen produced, bringing it to a purity level of 99.999% (H_2O impurities < 5ppm).

In the purifier, any oxygen present in the hydrogen flow reacts with the hydrogen itself, forming water again. The water resulting from the oxygen reaction and any traces of moisture from the process are then condensed in cooling batteries and discharged outside the hydrogen circuit. The hydrogen is conveyed to the buffer, then to the compressor and final high-pressure storage. The oxygen is dispersed freely into the atmosphere.

The electrolyzer and auxiliary systems are suitable for outdoor installation in a ventilated and/or air-conditioned ISO container. The production module includes the stack, the water treatment system, the power supply system (dedicated rectifiers and transformers), the cooling unit, and the Purification and Drying Unit (PDU). The instrument air compression system and auxiliary systems are shared with the other machines in the plant.

Electrolyzer power	kVA	1700
Transformer voltage	V	20,000
Auxiliary power	kVA	25
Auxiliary power supply voltage	V	400
Nominal hydrogen production	Nm3/h	200 / 196
Nominal Oxygen Production	Nm3 /h	100
Hydrogen Purity	%	> 99.8 / > 99.999
Oxygen purity	%	> 99.5
Production Pressure	barg	29
Consumption of demineralized and purified H_2O	l/h	200

Table 4 Technical characteristics of the electrolysis system

For the development of the project, De Nora worked in close synergy with the partners, coordinating all key activities to ensure effective integration of the different packages. Together, the team defined the water supply system for electrolysis, assessing available sources, treatment requirements, and process compatibility.

Since joining the project, De Nora has carried out a series of technical, engineering, and operational tasks necessary for adapting the 1 MW system to the Hy2Market project. Such as:

- Adaptations to the water treatment system, necessary to ensure compliant feedwater supply to the larger electrolyzer;
- Adjustments to the hydrogen purification and outlet treatment, required for safe and efficient downstream integration with the rest of the plant and the Peaker turbine

The collaboration also enabled the optimization of the site layout, including civil works and container positioning, taking into account operational constraints, accessibility, and maintenance needs.

In addition, a joint engineering effort was carried out for the process interconnections between the De Nora electrolyzer and the partners' equipment, defining interfaces, operating conditions, and connection lines.

Finally, the team developed the control system for the integrated configuration, with a focus on the interface between packages and the definition of signal exchange methods, ensuring coordinated, stable, and safe plant operation.

Detailed engineering has been completed. Packages production is scheduled for completion by the end of February 2026. Container assembly will then begin, with installation expected by the end of spring.

The electrolyzer must be supplied with a constant flow of water of a specified purity. Demineralized water suitable for the electrolysis process is prepared by the electrolyzer itself using a reverse osmosis system. The electrolyzer's purification system is supplied with raw water drawn from a water reserve consisting of four 5,000-liter tanks. These tanks will preferably be supplied with water from the aqueduct and, in cases of water shortage, can be filled with the aid of tankers. The size of the water reserve is calculated so that there is enough water for a batch of hydrogen production that completely fills the storage tank with approximately 200 kg of hydrogen.

The electrolyzer may experience fluctuations in its production flow rate. A low-pressure buffer tank is installed between the outlet section of the electrolysis system and the compression system to prevent large variations in flow at the compressor inlet. This buffer tank has a volume of approximately 1600 liters and an operating pressure of up to 30 bar.

4.2. High-Pressure Compression and Storage System

Due to the low density of hydrogen under standard conditions, the gas must be compressed to avoid the need for transporting or storing excessively large volumes. For safety reasons, the compressor is installed inside a dedicated bunker. Its purpose is to increase the pressure of the hydrogen produced by the electrolyzer—from 30–35 barg up to 200 barg (the operating pressure selected for this plant)—in order to fill six 2,335-liter cylinders.

The compression system is capable of handling the entire hydrogen flow generated by the electrolyzer and delivering it at 200 barg. Positioned downstream of the buffer tank, the compressor is an oil-free, piston-type unit powered by the hydrogen produced by the electrolyzer at a pressure of approximately 29 barg. Its role is to compress the hydrogen to 200 barg so that it can be transferred to the storage system. The use of oil-free technology prevents any lubricant from entering the hydrogen stream, even in the event of compressor malfunction.

To comply with the temperature limits specified in the technical documentation of the storage cylinders, the compression unit is equipped with a dedicated cooling circuit featuring a water-to-air heat exchanger. In accordance with the requirements of the Decree of July 7, 2023, governing hydrogen installations, the compressor must also be provided with adequate shielding to protect surrounding areas and contain the effects of any potential explosion. For this reason, as described in the previous section, the compressor will be installed inside a reinforced concrete bunker.

Suction pressure	bar	29

Discharge pressure	barg	200
Installed power	kW	30
Max. flow rate	Nm3 /h	220

Table 5 Hydrogen compressor characteristics

The proposal concerns the construction of a hydrogen storage system designed in accordance with PED and EN 13445 standards, ensuring a high level of safety and full compliance with current regulations. The system is engineered to operate at a design pressure of 240 bar.

Each container (cylinder) has an outside diameter of 559.0 mm and a maximum length of 11,800 mm, with a maximum internal volume of 2,335 liters and a maximum weight of 3,504 kg per unit. These specifications allow for the storage of up to 33.81 kg of hydrogen per cylinder, for a total system capacity of 202.88 kg.

To enhance durability and long-term resilience, the cylinders will be coated with a C4H protective system compliant with ISO 12944, providing effective corrosion resistance in harsh industrial environments. The closures will feature steel end caps, which can be configured either as two operational caps or as one operational and one blind cap, depending on specific operational needs.

The cylinders will be assembled into a single structure comprising six units, optimizing space utilization within the facility. This configuration not only maximizes storage safety and efficiency but also facilitates maintenance and inspection of individual components.

The storage system will include separate connections for hydrogen inlet and outlet, enabling simultaneous filling and discharging. This arrangement also allows for proper flushing and the safe removal of residual hydrogen during maintenance activities.

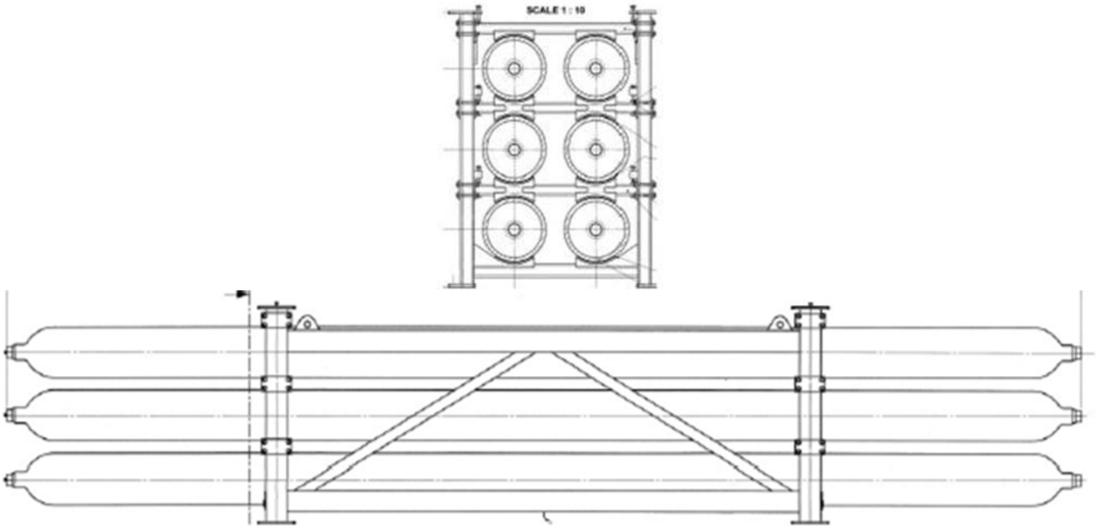


Figure 9: High-pressure hydrogen storage

4.3. H2 (Hydrogen) - CH4 (Methane) MIXER

A bypass will be installed on the methane line to mix the two gases.
A static mixer is inserted into this secondary branch of the methane line (which can be shut off at any time) to receive the hydrogen from the storage facility. The mixer has the function of homogenizing the mixture of hydrogen and methane by generating strong turbulence in the flow of the two gases. The output is conveyed to the Peaker plant's fuel system. This mixer will be equipped with:

- Pressure regulator at the hydrogen line inlet;
- Shut-off valves at the hydrogen inlet;
- Shut-off valve at the natural gas inlet;
- Pressure measurement systems using pressure transducers and pressure gauges;
- Modulating valves for hydrogen and natural gas flow;
- Shut-off valve at the mixed gas outlet.

The mixer will be connected to a mixture analysis system in order to measure the percentage of hydrogen in the mixture and modulate this percentage according to user requirements. The mixer design is reported in figure 19 where the magenta pipe represents the hydrogen line.

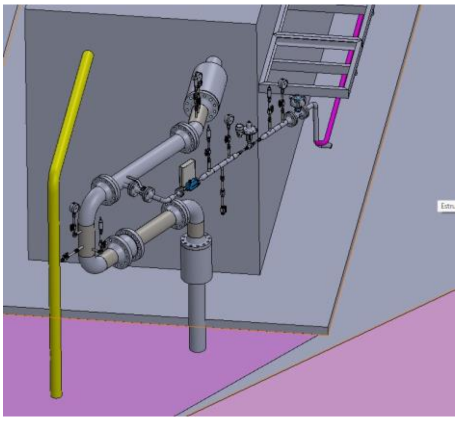


Figure 19 View of REMI cabin with SNAM inlet pipe and point of hydrogen/natural gas blending

4.4. Design of the Piping Distribution

4.4.1. Hydrogen Piping

The pipes used to construct hydrogen distribution systems are designed in accordance with current industry regulations. All hydraulic systems are designed to minimize pressure drops in the transported fluid, considering a maximum speed of 25 m/s and a maximum target operating speed of 10 m/s. The layout complies with minimum safety distances.
The system must be designed and certified in accordance with Directive 2014/68/EU - PED.

With reference to document "Hy2Market-PFD-4A," the flows and pressures are reported below in order to determine a final design for the piping.

For the checks on each section of pipe, the estimated nominal flow data, length, and section of the line are reported. The lengths provided are estimates and the assumed routes are preliminary and may therefore be subject to change during the execution phase depending on the final routes. The input data required to perform the checks include not only the length and flow rate of the pipeline but also the physical data of the fluid distributed (density, dynamic viscosity, and pressure).

Shut-off valves will be installed along the pipeline, and the hydrogen pipeline exiting the storage system will be above-ground for the first section and then cross the plant underground.

Line	Flow [Nm3/h]	Line length [m]	Line pressure [bar]	Pipeline ["]	Flow velocity [m/s]
Electrolyzer - Buffer	**200**	**15**	**29**	**3/4**	**9.48831391**
Buffer - compressor	**200**	**15**	**29**	**3/4"**	**9.48831391**
Compressor - tank	**200**	**15**	**200**	**1/2**	**2.993777572**
Tank section - Adjusted	**2325**	**5**	**200**	**1/2**	**34.80**
Tank - Mixer	**2325**	**200**	**28**	**1 1/2"**	**26.02571979**

Table 6 Hydrogen plant pipes sizing

4.4.2. Fluid Distribution Networks

Feed water, waste water, etc.) for the interconnection of all plant components and systems (including all necessary accessories, such as: racks, brackets, supports, manual valves, bends, reducers, vents, expansion joints, sockets for sensors and instruments, etc.);

Pipe crossings will be made inside underground tunnels protected on top by grates or drive-over hatches or buried underground. Their geometry and layout must be such as to allow the installation

4.4.3. Nitrogen Storage and Distribution System

There will be a gaseous nitrogen distribution system for inerting and emptying. Storage will consist of an appropriate number of cylinder packs.

The main functional and construction characteristics are as follows:

- Purpose: Purge circuits and equipment to ensure inert atmospheres prior to maintenance.
- Source: 110-200 barg bundle cylinders.
- Decompression and distribution panel to lines
- Distribution network: 316L stainless steel pipes, double ferrule fittings (Swagelok or equivalent).

4.4.4. Instrument Air Generation System

An instrument air generation system will be required to operate valves and actuators. If it is not possible to draw on the central compressed air circuit, an air compressor (complete with dryer, tanks, and all necessary accessories) will be provided to manage the compressed air requirements of the entire system. The compressed air distribution network can be buried underground or use the conduits intended for electrical cables or the nitrogen and hydrogen pipe tunnel.

4.4.5. Shut-Off, Relief, and Safety Valves

All main equipment will be connected to each other with special piping. In addition to local monitoring on each machine performed by the automation system, safety valves will be installed to automatically release excess pressure.

4.5. Functional Requirements and Design Data

- The materials of all H2 plant components and systems must be selected taking into account the phenomenon of hydrogen embrittlement and considering the problems of permeability, porosity, fatigue, and aging. It is recommended that the choice be based on ISO 11114-4.
- All technical requirements to prevent fires as set out in the Ministerial Decrees of October 23, 2018, and July 7, 2023, will be implemented.
- A classification of hazardous areas will be made in accordance with the ATEX directive. All components and systems of the H2 Plant must be ATEX certified according to their location within the H2 plant.
- All components and systems of the H2 Plant must be equipped with all the devices and instrumentation necessary to ensure optimal operation, in compliance with current safety regulations.
- The devices and instrumentation shall be of high quality, compliant with current regulations, certified, up to date (to ensure the availability of spare parts), and optimized for maintenance.

4.6. Complementary Works and Accessories

The entire hydrogen production facility will include services, systems, and structures that are not directly involved in the hydrogen production, compression, and storage process but are necessary to ensure the proper operation and safety of the production site:

- Grounding network: copper braids left at ground level at the main structural elements.

- Supply of shutdown and cooling systems.
- External flame detection system in addition to those already provided for the hydrogen production plant.
- Civil works (asphalting, reinforced concrete walls, foundations, and excavations).
- Video surveillance system and related cabling.
- Internal and external lighting system.
- Intrusion detection systems.
- Safety signs and signage.
- Road signs and signals.

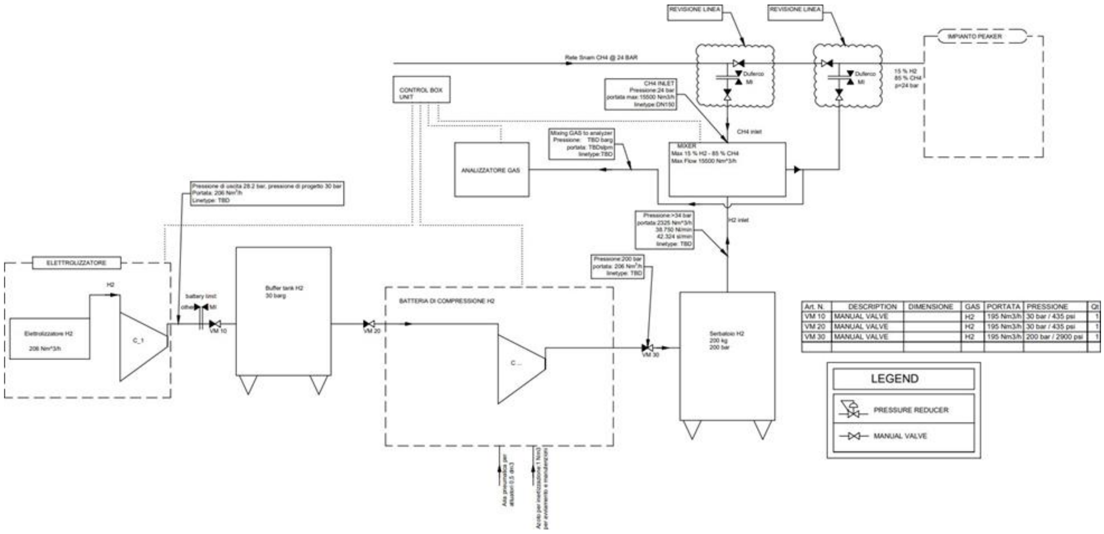


Figure 20 Plant PFD

4.6.1. Secondary Products of the Process

ATMOSPHERIC EMISSIONS

Emissions into the atmosphere will occur at a sufficient height so as not to pose a danger to people and equipment in the event of ignition.

The emission points are as follows:

Emission point	**Type of emission**	**Entity**	**Duration**	**Frequency**
Electrolyzer	Hydrogen/ Nitrogen	100 Nm^3/h	15 minutes	In case of extraordinary maintenance
Electrolyzer	Oxygen	100 Nm^3/h	When in operation	When in operation

Buffer tank	Hydrogen/ Nitrogen	9 Nm^3/h	30 minutes	In case of extraordinary maintenance
Compressor	Hydrogen/ Nitrogen	1 Nm^3/h	10 minutes	In case of extraordinary maintenance
Storage tanks	Hydrogen/ Nitrogen	100 Nm^3/h	1 hour	In case of extraordinary maintenance

Table 7 Summary of hydrogen production plant emissions

The nature and extent of the emissions do not pose a danger to plant operators or the surrounding areas.

4.6.2. Water Supply

The water needed for hydrogen production will be supplied by the municipal water system serving the industrial area. To compensate for any supply disruptions involving reduced flow or temporary interruptions, a 20,000-liter water reserve consisting of four 5,000-liter polyethylene tanks will be set up.

The buffer tanks will be equipped with:

- Visual and electronic level indicators
- Manual shut-off valves
- Overflow systems connected to safe drainage

This water will be used to feed the electrolyzer, which will first subject it to a reverse osmosis process, releasing approximately 0.5 m^3/h of waste water with a dissolved salt content almost double that of the water originally taken from the aqueduct.

4.6.3. Noise

With regard to noise emissions, the lot subject to intervention, as shown in the planimetric extracts, is included in area classified as V - Predominantly industrial areas. These are areas where, pursuant to the Prime Ministerial Decree of December 5, 1997, emission values are between 70 dB during the day and 60 dB at night, while emission values are between 65 dB during the day and 55 dB at night. The main sources of noise within the hydrogen production plant are as follows:

- Hydrogen compressor
- Hydrogen compressor air cooler
- Electrolyzer
- Electrolyzer air cooler.

All equipment must have a noise level of less than 75dB at a distance of 1m and at a height of 1.5m above the ground. This sound pressure level should result in noise levels of less than 56dB at the safety distances already prescribed for the outside.
In addition, the perimeter of the lot where the new plant will be built will be enclosed by a closed wall, which will further contribute to reducing noise towards the outside.

5. Modelling and simulation of the blending H2/NG combustion

Topics covered in this chapter:

- Description of the problem to address
- Model developed for blend combustion
- Kynetics
- Geometry
- Simulation

5.1. Problem Statement Description

The study reported on this section has been developed to assess the emissions of NOx, CO, and CO_2 downstream of the combustion chamber of the “peaker” turbine installed in the national electrical grid balancing plant owned by Duferco Sviluppo S.p.A., part of the Duferco Group, located in the Giammoro district of the Municipality of Pace del Mela (ME). The assessment is carried out when the turbine operates under conditions corresponding to the use of a fuel mixture composed of natural gas and hydrogen, with an H_2 content equal to 15% by volume.

The SGT-A65 WLE turbine (Figure 21), manufactured by Siemens AG, is a high-efficiency aeroderivative gas turbine. It is equipped with a dual cooling system: the first cooling stage occurs during the compression phases and is intended to cool the air entering the combustion chamber. The second cooling stage (WLE) takes place during combustion to prevent temperature rise and uncontrolled NOx formation. The turbine is also equipped with 24 burners. The injection of cooling water occurs through the same nozzles used for fuel injection.

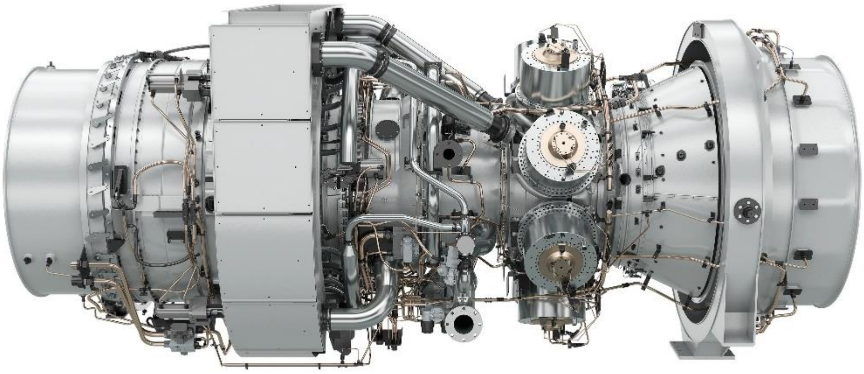


Figure 21 SGT-A65 turbine

For this purpose, a multi-physics model was developed and validated using experimental data collected during the operation of the plant when fueled exclusively with natural gas, with the aim of predicting the expected emissions under operating conditions involving the new fuel mixture. The model is intended to simulate only the combustion process within the aforementioned chamber.

The model was implemented and solved in COMSOL Multiphysics version 6.2, a finite-element simulation software for computational fluid dynamics problems.

This report systematically describes all the activities carried out for the development of the study, starting from the selection of the multi-physics model to the construction of the geometry and the definition of the assumptions required in cases where the available information was incomplete or missing.

Finally, the results of the two simulations carried out are presented and analyzed:

- the first, performed using only natural gas, which serves as a reference for comparison with the actual operating data of the turbine;
- the second, conducted with a mixture containing hydrogen (H_2 blend), aimed at estimating the outlet concentrations of NO_x and CO from the combustor.

5.2. Description of the Model Developed

The combustion of chemical species can be modeled through the formulation of a reactive turbulent flow, in which the balance equations (*The continuity equation, the momentum equations of Navier–Stokes, the heat transfer or energy balance equation, and the molar balance equation of the species involved*) are coupled using the Kays–Crawford model. The thermophysical properties of the fuel–oxidizer mixture and the reaction products were calculated using thermodynamic correlations. The mixture was assumed to be ideal and incompressible.

Continuity equation

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{u}) = 0$$

Momentum equations (Navier–Stokes)

$$\frac{\partial(\rho\boldsymbol{u})}{\partial t} + \nabla\cdot(\rho\boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla\cdot\tau + \rho\boldsymbol{g}$$

Heat transfer or energy balance equation

$$\frac{\partial(\rho E)}{\partial t} + \nabla\cdot\big(\boldsymbol{u}(\rho E + p)\big) = \nabla\cdot(\tau\cdot\boldsymbol{u}) - \nabla\cdot\boldsymbol{q} + \dot{Q}_{chimica}$$

Molar balance equation of the i-species involved

$$\frac{\partial(\rho Y_i)}{\partial t} + \nabla\cdot(\rho Y_i\boldsymbol{u}) = -\nabla\cdot\boldsymbol{J_i} + \dot{\omega}_i$$

Since the phenomena occur under turbulent conditions, the standard equations are modified by replacing the velocity, pressure, temperature, and concentration fields with their corresponding time-averaged variables, which account for both the temporal mean and the fluctuations. Introducing these corrected variables into the balance equations generates additional terms that require the adoption of specific models for their resolution.

$$\boldsymbol{u} = \overline{\boldsymbol{u}} + \boldsymbol{u}'$$

$$\boldsymbol{p} = \overline{\boldsymbol{p}} + \boldsymbol{p}'$$

$$\boldsymbol{T} = \overline{\boldsymbol{T}} + \boldsymbol{T}'$$

$$\boldsymbol{Y_i} = \overline{\boldsymbol{Y_\imath}} + \boldsymbol{Y_i}'$$

Random average Navier-stokes (RANS):

$$\frac{\partial(\bar{\rho}\overline{\boldsymbol{u}})}{\partial t} + \nabla\cdot(\bar{\rho}\overline{\boldsymbol{u}}\overline{\boldsymbol{u}}) = -\nabla\bar{p} + \nabla\cdot(\bar{\tau} - \overline{\rho\boldsymbol{u}'\boldsymbol{u}'}) + \bar{\rho}\boldsymbol{g}$$

To resolve the Reynolds stress tensor, a turbulence model is required to describe the formation and dissipation of the turbulent eddies hypothesized by Kolmogorov, enabling the calculation of turbulent viscosity. The k–ω model proves particularly suitable for studying complex flows, such as those occurring in combustion processes, which are characterized by curvature, separation, and recirculation. This model introduces two additional balance equations: one for the turbulent kinetic energy (k) and the other for the specific turbulence dissipation rate (ω), associated with energy dissipation.

$$\mu_t = \rho \frac{k}{\omega}$$

The remaining balance equations in the Reynolds-averaged formulation can be written as follows.

Continuity equation

$$\frac{\partial \bar{\rho}}{\partial t} + \nabla \cdot (\bar{\rho}\bar{\boldsymbol{u}}) = 0$$

Heat transfer or energy balance equation

$$\frac{\partial(\bar{\rho}\bar{E})}{\partial t} + \nabla \cdot \left(\bar{\boldsymbol{u}}(\bar{\rho}\bar{E} + \bar{p})\right) = \nabla \cdot (\bar{\tau} \cdot \bar{\boldsymbol{u}}) - \nabla \cdot (\bar{\boldsymbol{q}} + \boldsymbol{q_t}) + \overline{\dot{Q}_{chimica}}$$

Molar balance equation of the i-species involved

$$\frac{\partial(\bar{\rho}\overline{Y_i})}{\partial t} + \nabla \cdot (\bar{\rho}\overline{Y_i}\bar{\boldsymbol{u}}) = -\nabla \cdot (\bar{\boldsymbol{J}}_{\boldsymbol{i}} + \boldsymbol{J_{i,t}}) + \overline{\dot{\omega}_i}$$

The turbulent species and heat fluxes depend on the turbulent viscosity calculated from the RANS formulation and the k–ω model, as well as on the turbulent Schmidt and Prandtl numbers, which are estimated by the Kays–Crawford model and set to 0.5 and 0.85, respectively.

$$\boldsymbol{J_{i,t}} = -\frac{\mu_t}{Sc_t} \nabla \overline{Y_i}$$

$$\boldsymbol{q_t} = -\frac{\mu_t c_p}{Pr_t} \nabla \bar{T}$$

The Kays–Crawford model also resolves the net production rate of the i-th species as influenced by turbulence through the EDC (Eddy Dissipation Concept) model. This approach assumes that combustion occurs primarily within micro-mixing zones of reactants, where mixing is intense and rapid. The chemical reaction rate is therefore limited by turbulence, that is, by the rate at which the reactants are mixed.

$$\overline{\dot{\omega}_i} = \rho \frac{\chi}{\tau} (Y_i^{eq} - \overline{Y_i})$$

The equilibrium concentration of the species is determined by the chemical kinetics and may correspond either to the thermodynamic equilibrium concentration (in the presence of fast kinetics) or to the final reaction state described by the Arrhenius law. The heat generated by the reaction, included in the energy balance, depends on the reaction enthalpy of the individual chemical transformations involved in the process.

A key issue to address concerns the combustion conditions in the presence of cooling water. In this specific case, no detailed information was available regarding the method and exact location of water injection inside the combustion chamber. Moreover, the two-phase modeling of such a system is currently limited from both a numerical and modeling standpoint, due to the high physical complexity of the phenomenon and the lack of reliable coupling models between the gas and liquid phases. For these reasons, a simplifying assumption was adopted, whereby a fraction of water in vapor form is introduced together with the fuel flow. The amount of injected water was determined based on the data provided by the turbine manufacturer.

5.3. Kinetics Involved in the Reaction

The combustion of natural gas can be represented through a set of elementary reactions, in order to assess how different fluid-dynamic conditions may influence both NOx formation and any potential incomplete combustion of the fuels. Natural gas is a mixture of light hydrocarbons (C1–C5), whose composition may vary depending on the extraction site. The plant under study uses natural gas supplied through pipelines owned by Snam S.p.A. For this gas, analyses were carried out to determine, in accordance with ISO 6976, the molar fractions of the individual hydrocarbons present in the mixture.

Compound	Molar fraction (%)
N2	**1,76535**
CO2	**1,3474**
CH4	**87,7707**
C2H6	**7,52075**

C3H8	**1,25345**
iC4H10	**0,116425**
nC4H10	**0,153725**
iC5H12	**0,033725**
nC5H12	**0,07705**
neoC5H12	**0**
C6+	**0,0476**

Table 8 Compounds molar fractions in the gas mixture

The partial reactions of the individual hydrocarbons were considered as irreversible, with negligible activation energy and very high kinetic constants, in order to simulate the spontaneous evolution of the mixture following ignition. The reactions involving nC_4H_{10} (normal-butane) and iC_4H_{10} (iso-butane), as well as those involving nC_5H_{12} (normal-pentane) and iC_5H_{12} (iso-pentane), were considered as single lumped reactions. This approximation is valid as long as ignition phenomena of the mixture are not being evaluated. Reactions involving possible traces of heavier hydrocarbons present in the gas (C_6^+) were neglected.

$$2\ CH_4 + 3O_2 \rightarrow 2CO + 4H_2O$$

$$2\ C_2H_6 + 5O_2 \rightarrow 4CO + 6H_2O$$

$$2\ C_3H_8 + 7O_2 \rightarrow 6CO + 8H_2O$$

$$2\ C_4H_{10} + 9O_2 \rightarrow 8CO + 10H_2O$$

$$2\ C_5H_{12} + 11O_2 \rightarrow 10CO + 12H_2O$$

$$2CO + O_2 \rightarrow 2CO_2$$

The formation of NOx was investigated using Arrhenius-type kinetics.

$$N_2 + O_2 \rightarrow 2NO$$

The differential equation used to describe the formation of the product species follows a logic consistent with chemical kinetics. The kinetic constants (k_i) are expressed according to an Arrhenius-type law. In the case of NOx formation, the kinetic parameters were taken from the literature, based on the mechanism proposed by Zeldovich [1].

With regard to carbon dioxide formation, the parameters were selected on the basis of certain assumptions aimed at ensuring the numerical convergence of the problem. In particular, since the analysis is carried out under steady-state conditions, the simultaneous injection of fuel and cooling water prevents the system from immediately reaching the typical combustion temperatures required to overcome the activation energy of the reaction.

In practice, water injection occurs with a certain delay, so that the resulting temperature reduction helps limit NOx formation without hindering the complete oxidation of the fuel to CO_2. To account for this difference between the model and real operation, the kinetics of carbon dioxide formation were suitably adjusted, while still ensuring a coherent representation of the overall process.

$$\frac{d[CO_2]}{dt} = k_1[CO][O_2]^{\frac{1}{2}}$$

$$\frac{d[NO]}{dt} = k_2([N_2][O_2])^{\frac{1}{2}}$$

$$k_i = AT^n \exp\left(-\frac{E_a}{RT}\right)$$

Reaction	Kinetic constant (k_i)	Activation Energy [J/mol]	Pre-exponential factor	Note
C1	$1*10^{100}$	-	-	Assumption
C2	$1*10^{100}$	-	-	Assumption
C3	$1*10^{100}$	-	-	Assumption
C4	$1*10^{100}$	-	-	Assumption
C5	$1*10^{100}$	-	-	Assumption
CO2	$1*10^{100}$	-	-	Assumption
NO	-	$3.18*10^5$	$9*10^8$	Ref. 1

Table 9 Reactions parameters

5.4. Geometry Configuration

The geometry, which in the simulation environment represents the control volume within which the combustion processes develop, was constructed starting from preliminary representations

provided by Duferco in a descriptive datasheet of the turbine (Figure 22), issued by the turbine manufacturer Siemens.
The same document reports the number of burners. However, detailed information regarding the geometry of the combustion chamber is missing. Since the available drawing is a sectional view, it is not possible to determine with certainty whether the configuration is annular or tubo-annular.

Furthermore, no data are provided concerning the fuel and water injection nozzles, nor the air-inlet configuration into the combustion chamber.

To overcome the lack of detailed information, it was necessary to introduce a series of simplifying assumptions, which led to the definition of a simplified axisymmetric planar geometry lying on the Orz plane of the computational domain, in order to reproduce the evolution of the combustion process as realistically as possible.

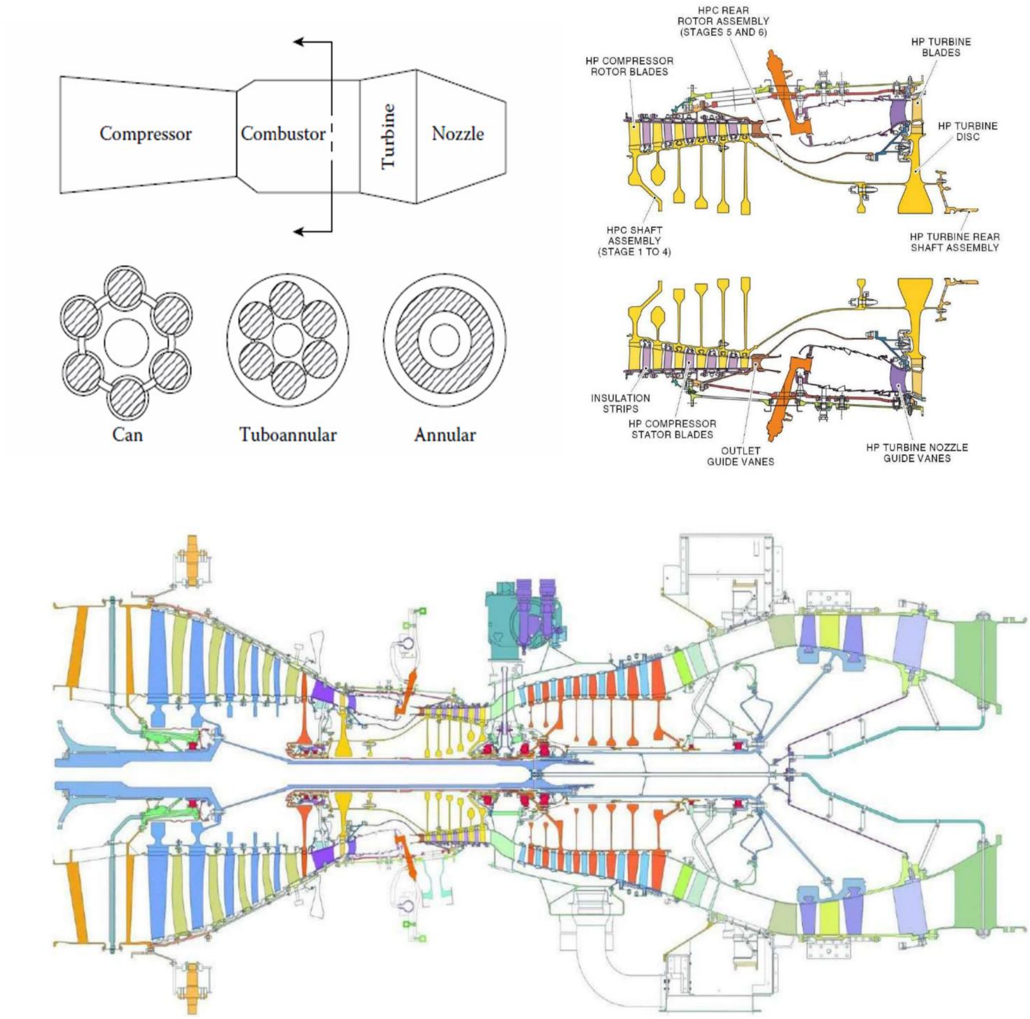


Figure 22 Sectional views showing the detailed geometry of the combustion chamber

The geometry (Figure 23) represents an axisymmetric section of a tubo-annular combustion chamber. Near the axis of symmetry (r = 0) is located the fuel injection nozzle, consisting of a tube with radius R=0.025 m. The nozzle, 0.02 m in length, features a slight inward deflection toward the center of the chamber, designed to enhance turbulence at the contact region between fuel and air and to promote the reactive processes described by the model.

The combustion air enters the chamber through two inlets: an axial one, aligned with the fuel nozzle (Re–Ri = 0.2 m), and an annular one surrounding the combustion chamber (Re–Ri = 0.1 m).

The annular section is connected to the chamber through two openings that allow air to enter and mix with the fuel already undergoing combustion, thereby generating an intermediate combustion zone and a final diffusion zone.

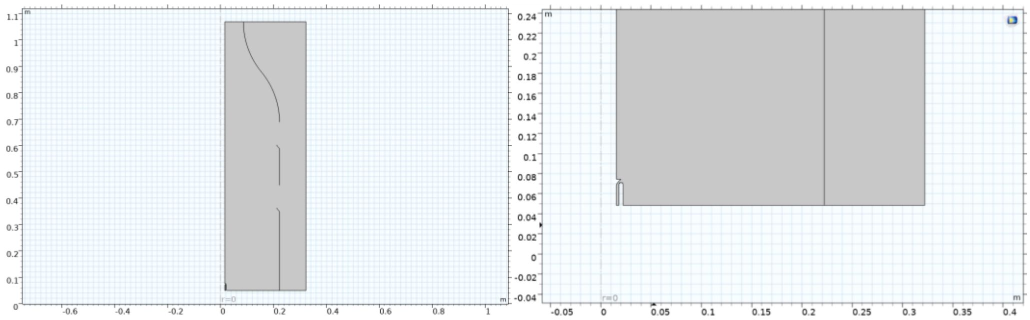


Figure 23 Simplified view of the combustion chamber with a detailed close-up of the nozzle (right)

5.5. Simulations Assumptions

In the absence of detailed information regarding the turbine operation and the internal geometry of the combustion chamber, several estimation-based considerations were developed to determine the characteristic velocities of the air and fuel flows within the individual combustion chamber. The turbine is designed to operate with an air-to-fuel ratio (A/F) up to 3.4 times the stoichiometric value. Considering methane (CH_4) as the only fuel, the stoichiometric ratio is equal to 17 kg of air per kilogram of fuel.

The total fuel mass flow supplied to the turbine is 11,737 kg/h, corresponding to 0.135 kg/s per burner (number of burners: N = 24). For a characteristic jet velocity of 76 m/s, typical of such applications, the fuel mass flow through the nozzle is approximately 0.1 kg/s, or 0.06 kg/s when accounting for water injection through the same nozzle—values in good agreement with those provided by the turbine manufacturer. For simplicity, a combined fuel-and-water mass flow rate of 0.1 kg/s per burner was therefore assumed for the calculations.

Under these operating conditions, the corresponding air mass flow rate—based on operation at three times the stoichiometric ratio—is 3.06 kg/s. To estimate the air velocity, the volumetric flow rate entering the combustion chamber must be known, which depends on the fluid density. However, since the simulation was performed considering only the pressure difference between inlet and outlet, and not the absolute pressure values, determining this flow rate precisely is challenging.

Therefore, the air density at atmospheric pressure was adopted as a reference. At this pressure, the air density is approximately 1.225 kg/m³, yielding a total volumetric flow rate of 2.498 m³/s. Assuming this flow is distributed between the two ducts with a 9:1 ratio, the resulting average velocities in the ducts are 20 m/s and 9 m/s, respectively, for the stoichiometric condition.

Additionally, the inlet temperature of both fuel and air was set to 500 K (227 °C). The corresponding mass fractions for the inlet streams are therefore as follows:

Compound	Mass fractions
H2O	**0,37**
CO2	**0,02**
CH4	**0,48**
C2H6	**0,077**
C3H8	**0,018**
C4H10	**0,00534**
C5H12	**0,0027**

Table 10 Compounds molar fractions in the simulated gas mixture

In the simulation with the blend, the mass flow rates were considered to be essentially identical, thus keeping the velocity values of both fuel and air constant. The only significant change concerned the definition of the mass fractions, which were adjusted to account for both the blend composition and the higher water content expected in the scenario under examination, as reported by the manufacturer’s data.

Compound	Mass fractions
H2O	**0,4**

CO2	**0,0185**
CH4	**0,444**
C2H6	**0,071**
C3H8	**0,016**
C4H10	**0,005**
C5H12	**0,0025**
H2	**0,002**

Table 11 Compounds molar fractions in the simulated blended gas mixture

5.6. Results of the Simulation with Natural Gas Only (Validation)

The simulations carried out using natural gas only were employed to calibrate the numerical model and verify its consistency with the experimental data provided by Duferco, collected during the commissioning phases of the turbine. The measurements (Work Order No. 496/23), performed by the Capone Lab laboratory located in Via delle Gelsominaie 31/33, 98057 Milazzo (ME), report the concentrations—expressed in ppm—of NO_x, CO, and other pollutants in the exhaust gases under operating conditions. These measurements cover both the transient phases of start-up and shutdown and the steady-state conditions (Figure 24), and refer to the gases leaving the turbine before the SCR abatement system.

Data on the gas temperature downstream of combustion are also available. For this parameter, neither the exact positioning of the thermocouples nor the total number of instruments installed is specified. Nevertheless, the three parameters—exhaust temperature, NO_x concentration, and CO concentration—were used for model validation. Experimental measurements indicate that the turbine exhaust gas temperature is 770 °C, while the steady-state NO_x and CO concentrations are 30 ppm and 20 ppm, respectively.

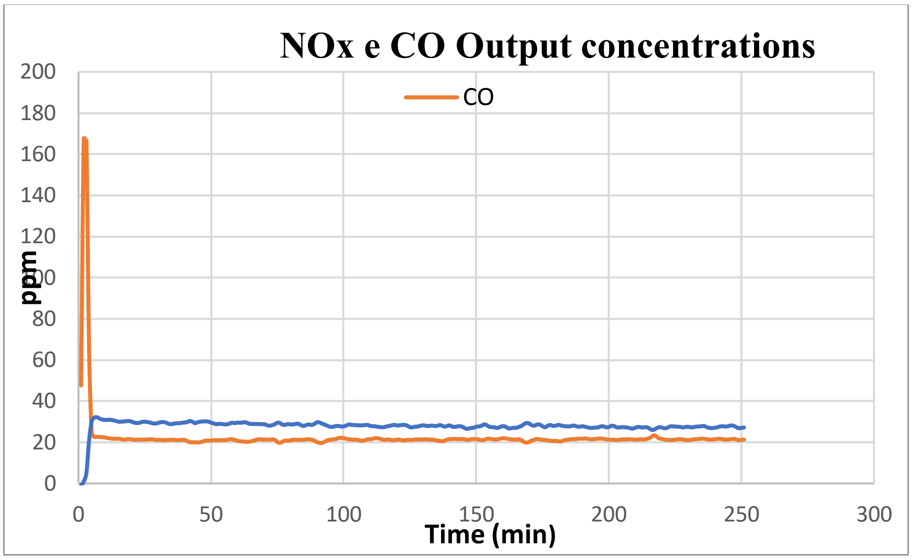


Figure 24 Pollutant concentration measurements in transient start-up phases and steady-state operation

The calculations for these parameters were performed along the outlet boundary of the combustor. Specifically, for each parameter, its distribution along the outlet profile was obtained; these distributions were then integrated over the entire extent of the boundary in order to determine the corresponding average value.

In mathematical terms, denoting by r the outlet boundary and by $\phi(r)$ the parameter under consideration (as a function of the radial coordinate), the average value was computed as:

$$\bar{\phi} = \frac{1}{L_t} \oint \phi(r) dr$$

where Lt is the length of the boundary.

An additional analysis was performed for the temperature. Considering the converging geometry of the duct and the presence of low-pressure regions indicative of possible backflow phenomena, the boundary integral was evaluated not only at the nominal outlet section but also at three characteristic upstream locations. This approach made it possible to examine the evolution of the thermal distribution along the final portion of the duct and to identify any significant variations caused by local pressure gradients.

$$\bar{T_\iota} = \frac{1}{L_{t,i}} \oint T(r) dr$$

The points Lt,i were identified by analyzing the trend of the relative pressure along the outlet section. Specifically, the relative-pressure curve along r was extracted, and from this distribution the locations exhibiting low-pressure regions—indicative of the onset of potential backflow—were identified. The characteristic distances therefore correspond to the points where the pressure gradient shows an inversion or a significant reduction compared to the expected profile (Figure 25).

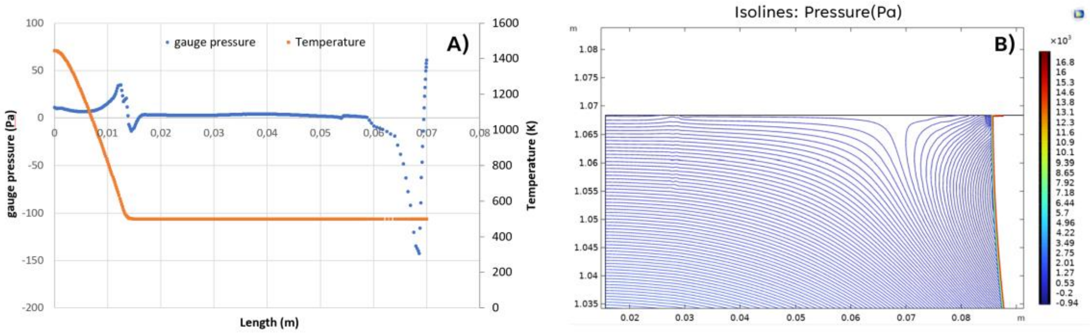


Figure 25 (A) Temperature and relative pressure profiles at the combustor outlet; (B) Pressure Isolines

The results of the analysis conducted on the parameters for which experimental data were available are therefore presented. For these quantities, the corresponding contour plots (Figures 26, 27) are also reported, which are useful for visualizing their distribution within the considered domain.

Variable	Models	Experimental	Relative error (%)
Temperature 1 [°C]	763	700-770 °[C]	< 1%
Temperature 2 [°C]	350	-	> 100%
Temperature 3 [°C]	334	-	> 100 %
NOx ppm	52,14 ppm	30 ppm	73 %
CO ppm	22,85 ppm	20 ppm	14%

Table 12 Simulation outcomes (natural gas only)

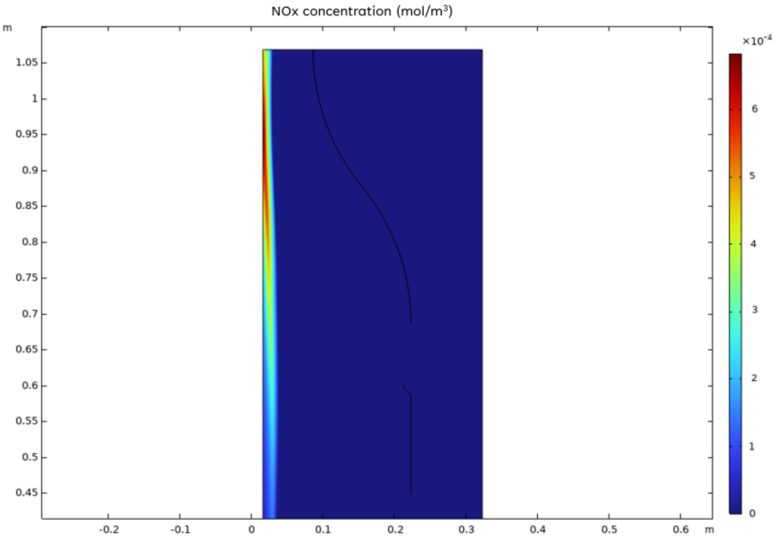


Figure 26 Contour plot of NOx concentration with natural gas only

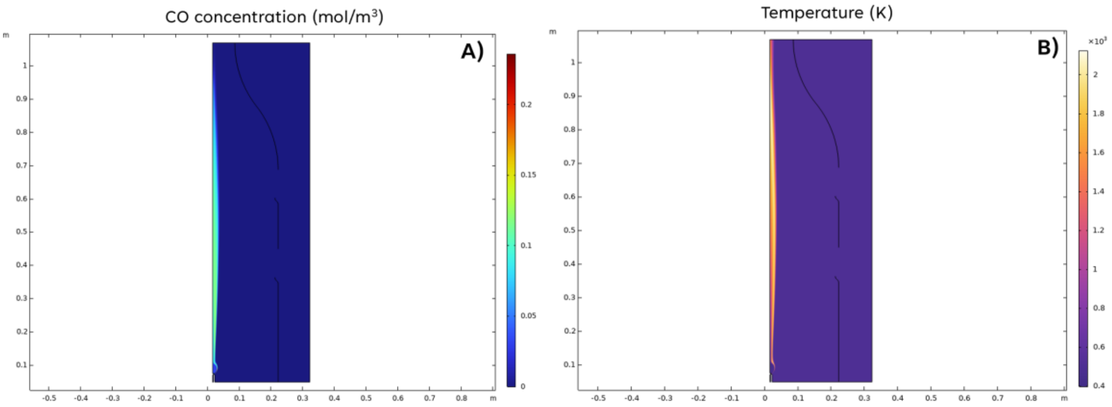


Figure 27 A) Contour plot of CO concentration with natural gas only; B) Contour plot of Temperature with natural gas only

5.7. Results of the Simulation with Blend Gn/H2 15%(V/V)

Using the same model, predictive simulations were performed on the parameters previously employed for validation, namely temperature and the concentrations (in ppm) of NOx and CO, in the case of blended gas operation. In addition, CO_2 values were calculated in order to verify and quantify the effective reduction achieved through the use of the gas mixture.

Variable	Natural Gas (GN)	GN/H2 15%(v/v)	Variation (%)
Temperature [°C]	763°[C]	720°[C]	-5,6 %
NOx ppm	52,14 ppm	45,14 ppm	-13,4 %
CO ppm	22,85 ppm	14 ppm	-38,7 %
CO_2 ppm	4628 ppm	4214 ppm	-8,9%

Table 13 Simulation outcomes (blended gas)

It should be noted that the hydrogen considered in this study is produced through a water electrolysis process using electrical energy and can therefore be reasonably approximated as pure hydrogen within the developed model.

The introduction of hydrogen as a partial replacement for methane in the combustion chamber leads to a significant reduction in CO formation at the outlet, due to the lower presence of carbon-based fuel. In addition, a lower outlet temperature and a decrease in NOx production are observed, indicating an overall improvement in the environmental performance of the combustion process. These results are consistent with findings reported in the literature[2], according to which hydrogen flames are more compact and shorter, with higher local temperatures. During natural gas combustion, the more extended high-temperature region is located near the outlet of the combustion chamber, whereas for hydrogen combustion the region of maximum temperature is found closer to the gas inlet, in correspondence with the incoming flow. This temperature distribution reflects the intrinsic differences in the combustion properties of the two fuels and explains the observed trends in CO and NOx formation.

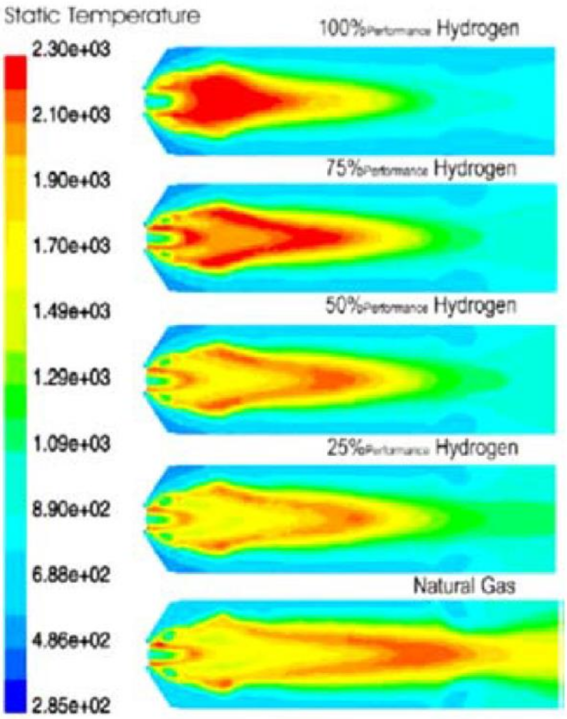


Figure 28 Contours of static temperature for natural gas, mixture and pure hydrogen taken from [2].

This behavior is also confirmed by the simulations. By analyzing the temperature distribution along the axis of symmetry in the two cases (Fig. 9), it can be observed that the curve corresponding to the blended fuel is flatter, with a lower maximum peak, while overall exhibiting higher temperatures. It is interesting to note that, although the introduction of hydrogen would be expected to increase the temperature in the central region, potentially leading to an increase in NOx formation, this effect does not occur. This is due to the injection of water at the inlet, which is effective in locally reducing the temperature and mitigating NOx formation in that region.

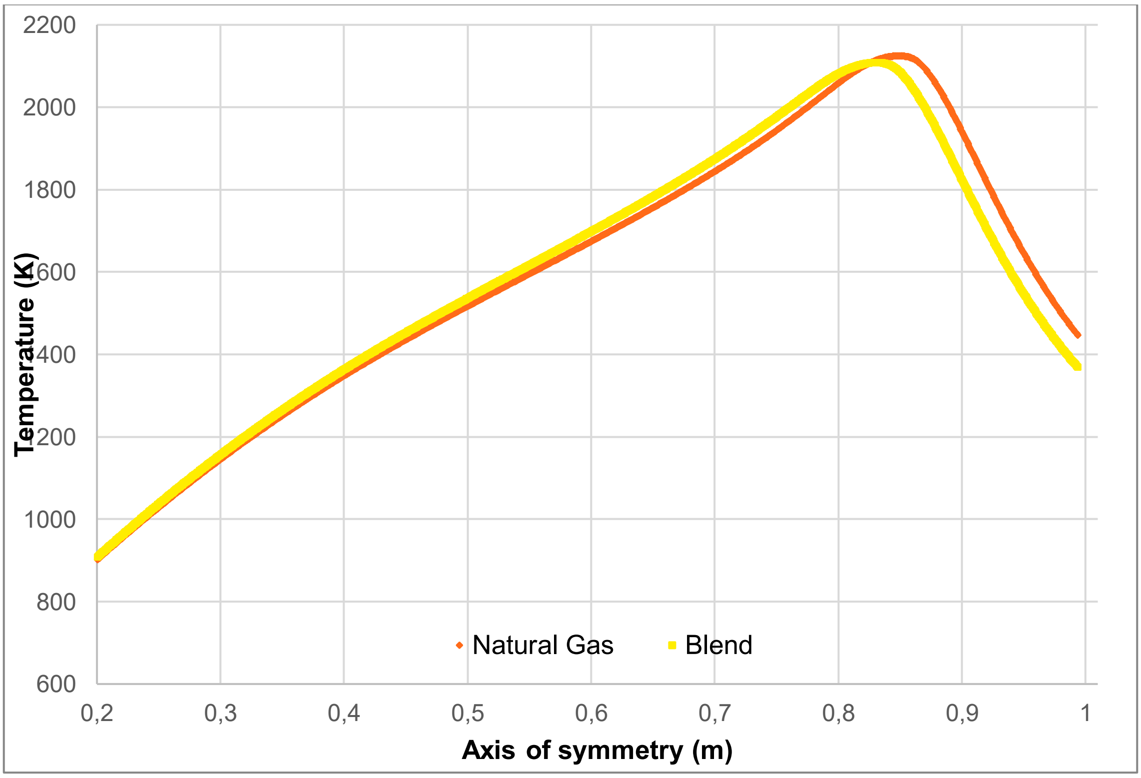


Figure 29 Axial temperature profile in the two investigated cases: natural gas (orange) and blend (yellow)

6. Conclusions

The Hy2Market Sicilian pilot represents a concrete and pioneering demonstration of the technical, regulatory, and operational feasibility of integrating green hydrogen into an existing industrial power generation asset dedicated to flexible electricity production. The deployment of the full system (1 MW electrolysis to be provided by De Nora, compression, high-pressure storage, and blending up to 15% hydrogen by volume into the fuel line of a 58 MW peaker turbine) stands among the first real-scale implementations in Europe within the peaking-plant sector, a segment traditionally difficult to decarbonize.

The extensive permitting, engineering, and safety activities led by Duferco and Power Evolution have confirmed that a hydrogen production facility can be effectively integrated within the Giammoro industrial area while ensuring full compliance with ATEX, PED, and the latest Italian fire-prevention regulations. Given the modest production capacity, neither an Environmental Impact Assessment nor an Integrated Environmental Authorization is required, further validating the project's regulatory sustainability. The resulting configuration ensures high safety standards, modularity, and replicability, supported by advanced automation systems and reinforced civil structures specifically designed for risk mitigation.

Computational fluid dynamics and thermochemical modeling performed by CNR-ITAE demonstrate that blending natural gas with 15% hydrogen yields clear environmental benefits: NO_x emissions decrease by approximately 13%, CO by nearly 39%, and CO_2 by roughly 9%, with a reduction of more than 5% in turbine outlet temperature. These improvements occur without compromising combustion stability or the operational flexibility required by grid-balancing services, confirming hydrogen’s viability as a decarbonization vector for dispatchable power generation.

With detailed engineering completed and installation planned for spring 2026, the pilot serves as a foundational milestone for the development of the Sicilian Hydrogen Valley and a reference model for other energy-intensive industrial sites. The involvement of SNAM further extends the strategic value of the project, enabling future replication across regional gas infrastructures, refineries, and petrochemical sites. Overall, the Hy2Market Sicilian pilot confirms that green hydrogen can be successfully integrated into complex energy systems, delivering tangible contributions to the decarbonization targets outlined in the European REPowerEU strategy

7. References

[1] *Zeldovich, Yakov BorisovichHG and Rashid A. Sunyaev. “25. The Oxidation of Nitrogen in Combustion and Explosions.” (1992).*

[2] *Serbin, Serhiy Ivanovich and Kateryna Burunsuz. “Numerical study of the parameters of a gas turbine combustion chamber with steam injection operating on distillate fuel.” International Journal of Turbo & Jet-Engines 40 (2020): 71 - 80.*