



Development of Hydrogen Injection and Mixing Systems in Natural Gas Networks

Gonçalo Martins Fernandes Mendes de Freitas

Master Dissertation

FEUP Supervisor: Prof. Dr. Abel Rouboa

PCV Supervisor: Eng. António Pereira

Master in Mechanical Engineering

September 2023

Abstract

The global environmental crisis has sparked significant debates, with a focal point on tackling greenhouse gas emissions. A multitude of strategies have been meticulously examined to curtail these emissions. Given that the majority of these gases stem from the combustion of fossil fuels, a straightforward path towards a more environmentally sustainable planet involves their substitution.

Hydrogen has emerged as a potential solution to address the pressing environmental challenge. This versatile gas holds the promise of serving as a primary energy source and a conduit for energy, distinct from fossil fuels, and boasts the advantage of being producible. Hydrogen can be generated through a range of chemical methods. Although its current production is largely reliant on fossil fuels, an alternative approach involves utilizing electricity to carry out water electrolysis. In an optimal scenario, hydrogen could achieve a completely green status, achieved through electrolysis powered by renewable energy sources like solar or wind power.

The practice of incorporating hydrogen into the natural gas (NG) mixture represents a strategic step towards gradually substituting fossil fuels. This research is chiefly centered on developing a project to refurbish a GRMS.

The creation of this system entailed a series of sequential stages. Commencing with the selection of suitable pipe materials, stainless steel emerged as the preferred choice. A meticulous assessment of two established hydrogen-compatible alloys, namely 304L and 316L, was conducted, resulting in the selection of the 304L alloy.

Subsequently, the development process proceeded to the formulation of a Piping and Instrumentation Diagram (P&ID). This initial phase necessitated the identification of the system's core modules indispensable for its optimal functionality. These encompassed the input module, filtration module, pre-heating module, pressure regulating module, metering module, and the output module.

In order to complete the P&ID, it was necessary to calculate the size of the pipes using the different pressures, temperatures and volumetric flow rates stipulated. Following this, the subsequent phase involved the meticulous selection of the station's various components, a pivotal measure to guarantee seamless operation. Simultaneously, the process encompassed the formulation of the ultimate budget required for the comprehensive refurbishment of the station.

Keywords: GRMS; greenhouse gases; natural gas; hydrogen.

Resumo

A crise ambiental mundial suscitou debates importantes, com destaque para a luta contra as emissões de gases com efeito de estufa. Foram examinadas meticulosamente várias estratégias para reduzir essas emissões. Dado que a maioria destes gases provém da combustão de combustíveis fósseis, um caminho direto para um planeta mais sustentável do ponto de vista ambiental passa pela sua substituição.

Desta forma, o hidrogénio surgiu como uma solução potencial para enfrentar o premente desafio ambiental. Este gás versátil promete ser uma fonte de energia primária e um condutor de energia, diferente dos combustíveis fósseis, e tem a vantagem de poder ser produzido. O hidrogénio pode ser produzido através de uma série de métodos químicos. Embora a sua produção atual dependa largamente dos combustíveis fósseis, uma abordagem alternativa envolve a utilização de eletricidade para realizar a eletrólise da água. Num cenário ideal, o hidrogénio poderia atingir um estatuto totalmente ecológico, conseguido através da eletrólise alimentada por fontes de energia renováveis, como a energia solar ou eólica.

A prática de misturar o hidrogénio com o gás natural (GN) representa um passo estratégico para a substituição gradual dos combustíveis fósseis. Esta investigação centra-se essencialmente no desenvolvimento de um projeto de reabilitação de uma GRMS.

A criação deste sistema envolveu uma série de etapas sequenciais. Começando pela seleção dos materiais adequados para as tubagens, o aço inoxidável surgiu como a escolha preferida. Foi realizada uma avaliação metódica de duas ligas estabelecidas compatíveis com o hidrogénio, nomeadamente 304L e 316L, resultando na seleção da liga 304L.

Subsequentemente, o processo de desenvolvimento prosseguiu para a formulação de um Diagrama de Tubagem e Instrumentação (P&ID). Esta fase inicial exigiu a identificação dos módulos principais do sistema, indispensáveis para o seu funcionamento ótimo. Estes englobam o módulo de entrada, o módulo de filtração, o módulo de pré-aquecimento, o módulo de regulação da pressão, o módulo de medição de caudal e o módulo de saída.

Para completar o P&ID, foi necessário calcular a dimensão das tubagens em função das diferentes pressões, temperaturas e caudais volumétricos estipulados. Seguiu-se a fase de seleção minuciosa dos vários componentes da estação, uma medida fundamental para garantir um funcionamento sem falhas. Simultaneamente, o processo envolveu a formulação do orçamento final necessário para a remodelação completa da estação.

Palavras chaves: GRMS; gases de efeito de estufa; gás natural; hidrogénio

Acknowledgements / Agradecimentos

Esta dissertação representa o final de uma etapa muito importante na minha vida. Hoje marca-se o desfecho de um longo caminho numa faculdade que tão bem me acolheu e que tanto contribuiu para a pessoa que sou hoje. Neste percurso somaram-se inúmeras aprendizagens e principalmente amigos que irei levar para o resto da vida.

À minha família, que sempre esteve do meu lado para me apoiar em todos os precalços que fui encontrando nesta caminhada e que me ensinaram a não ter medo de enfrentar novos desafios fazendo de mim uma melhor pessoa e mais preparada para enfrentar a vida. Aos conhecimentos de bricolage transmitidos pelo meu Pai que sempre me fizeram interessar pelo funcionamento dos “gadgets” e que fez despertar em mim o interesse pela engenharia. À minha Mãe por todas as trocas de olhares que acabavam em gargalhadas e se tornaram em momentos inesquecíveis, às palavras de consolo e amor incondicional que só uma mãe sabe dar. À minha irmã por todas as “dores de crescimento” que serviu para tornarmos a nossa relação ainda mais forte mas, acima de tudo, um obrigado por me ter dado uma sobrinha maravilhosa que deixa o tio babado. À minha Tia Gabriela que sempre foi como uma segunda mãe para mim e que com os seus cozinhados e conselhos me foi dando sempre força quando mais precisava para me superar.

À minha namorada Francisca, por ter aparecido no momento certo e não ter feito de mim o tio solteiro que a minha irmã sempre achou que iria ser. Por todas as palavras de apoio e conselhos nos momentos mais complicados, que me ajudaram a ver que há sempre um lado positivo mesmo nas situações mais difíceis.

Aos meus amigos, que sempre me acompanharam nas jantaras, festas e viagens que fizeram desta uma das melhores fases da minha vida, com momentos de diversão que sei que irei levar para sempre comigo.

Por fim, gostaria de agradecer ao Sr. Eng. António Pereira pela oportunidade que me deu de estagiar na PCV e que me propôs este desafio. Ao Sr. Arquiteto Pedro Nunes e à Eloisa Cunha por todo o tempo dispensado comigo e pelo apoio incondicional que me deram ao longo deste projeto. E ao meu orientador Prof. Dr. Abel Rouboa, que sempre esteve disponível durante todo este percurso.

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Acronyms

AEL- Alkaline electrolysis
AEM- Alkaline anion exchange menbrane
CCS- Carbon capture anda storage
EU- European union
FIR- Flow indicator recorder
FQIR- Flow quantity indicator recorder
GHG- Greenhouse gas
GRMS- Gas regulation and measurement station
LNG- Liquified natural gas
NG- Natural gas
PCV- Pressure control valve
PDI- Pressure differential indicator
PDIT- Pressure differential indicator transmitter
PEM- Polymer electrolyte menbrane
PI- Pressure indicator
PIT- Pressure indicator transmitter
PLC- Progammmable logic controller
PSV- Pressure safety valve
P&ID- Piping and instrumentation diagram
REN- Redes energéticas nacionais
SMR- Steam methane reforming
SOEL- Solid oxid electrolysis
SSV- Slam shut valve
TE- Temperature element
TI- Temperature indicator
TIT- Temperature indicator transmitter
TT- Temperature transmitter
TW- Thermowell
WGS- Water gas shift
XA- Unclassified alarm

Symbols

DN_{req}	Required nominal size	[mm]
P_f	Fluid pressure	[bar]
T_f	Fluid temperature	[°C]
T_{final}	Final temperature	[°C]
$T_{initial}$	Initial temperature	[°C]
U_{max}	Maximum fluid velocity	[m/s]
$\dot{V}_{H_2}$	Volumetric flow rate of hydrogen	[Nm ³ /h]
$\dot{V}_{NG}$	Volumetric flow rate of natural gas	[Nm ³ /h]
$\dot{V}_{Total}$	Total volumetric flow rate	[Nm ³ /h]
%H ₂	Volumetric fraction of hydrogen	[%]
ΔT	Temperature variation increasing	[°C]
$\Delta T_{cooling}$	Cooling temperature variation	[°C]

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1 Introduction

1.1 Contextualization - importance of the study

At present, the global community faces a critical crisis concerning climate change, primarily triggered by the heightened concentration of greenhouse gases (GHG) within the atmosphere. These gases can originate from both natural sources and human endeavors.

Numerous research efforts have been undertaken to comprehend the primary drivers behind the escalating presence of GHGs in the atmosphere. These endeavors also aim to pinpoint the activities that have played a pivotal role in exacerbating this phenomenon. Consequently, it has been established that the emission of greenhouse gases is substantially attributed to human activities. Among the various human actions, notable contributors include deforestation and the amplified utilization of fossil fuels.

Following the advent of the industrial revolution, there was a pronounced surge in the utilization of fossil fuels. By 2010, approximately 80% of the world's primary energy consumption was derived from the combustion of these finite resources. This circumstance has led to grave repercussions concerning the escalation of greenhouse gases within the atmosphere.

For this reason, the adoption of renewable energies emerges as the paramount alternative for curtailing and ultimately discontinuing the reliance on fossil fuel consumption. Across the globe, an increasing number of studies and discussions are being conducted to discern the most pragmatic path towards this gradual transformation. To achieve this transformation, distinct substitutes must be devised for each fossil fuel category, encompassing natural gas, petroleum derivatives, and solid fuels.

With regards to natural gas (NG), a particularly promising substitute gaining traction is the integration of hydrogen. Numerous investigations have been undertaken to assess the viability of this transition, and two principal paths have surfaced: the establishment of a hydrogen network akin to the existing natural gas infrastructure or the incorporation of hydrogen into the current natural gas grid. Given the considerable cost associated with building a hydrogen network from scratch, the main objective has focused on mixing hydrogen with the existing natural gas network by making modifications to the current natural gas network so that it can support hydrogen.

Consequently, the methodical infusion of hydrogen directly into the natural gas network is under scrutiny, aiming to harness the preexisting infrastructure while simultaneously diminishing the carbon footprint. This approach entails a gradual amalgamation of the two gases, commencing with lower hydrogen concentrations and progressing until natural gas is entirely substituted.

With the aforementioned aim in sight, the European Union (EU) has established targets for diverse nations, centered on the reduction of natural gas utilization and its substitution with hydrogen by 2030(1). In line with this trajectory, REN has put forth a proposition to PCV. The proposal suggests the revitalization of the natural Gas Regulation and Measurement Station

(GRMS) located in Valongo. This proposed renovation aims to adapt the station to accommodate a mixture of natural gas and hydrogen of up to 20%.

1.2 Overview of the company

PCV Gas Solutions is a Portuguese enterprise located in Porto. This company was founded in 2004 under the guidance of engineer António Pereira and currently has a team of 5 professionals. PCV operates as a specialized entity, providing comprehensive technological solutions encompassing Systems and Networks tailored for natural gas, hydrogen, biomethane, and other sustainable gases.

The company holds notable distinctions, serving as a representative for industry giants such as Honeywell and RMG in Portugal, among other affiliations. Duly accredited as a qualified service provider and supplier, PCV caters to key stakeholders in the Portuguese natural gas sector, including REN and GALP.

Central to its portfolio, PCV offers a diverse spectrum of solutions spanning regulation, measurement, filtration, heating, control, and gas analysis. These solutions cater to both industrial clients and natural gas utilities. The company is recognized for its role in conceiving, designing, and executing turnkey systems and networks for natural gas, tailored to the specific requirements of clients on a demand basis.

1.3 Objectives of the project

The primary objective of this dissertation is to revamp a GRMS capable of accommodating a blend of natural gas and hydrogen.

To accomplish this goal, the initial step involves gaining a comprehensive understanding of the predominant solutions currently available in the market. Following this, the process shifts towards defining the system's prerequisites, encompassing critical aspects such as optimal pressures, temperatures, and requisite valves imperative for the seamless operation of the station.

Subsequently, the focus shifts to the creation of a Piping and Instrumentation Diagram (P&ID) for the GRMS, along with strategizing the implementation of actions that necessitate control via a Programmable Logic Controller (PLC).

Ultimately, a pivotal task is to appropriately size the pipelines, carefully select the suitable materials, and precisely choose the specific components. These steps are crucial for compiling a comprehensive budget that accurately reflects the cost estimation.

1.4 Structure of the dissertation

The dissertation is structured in four distinct chapters. In Chapter 1, a succinct contextualization of the dissertation's theme is provided to establish the significance of transitioning from the prevailing primary energy source to an alternative, namely hydrogen. Additionally, an introduction to the company is furnished, and the dissertation's overarching objectives are clearly delineated.

Chapter 2 is dedicated to an extensive literature review concerning the central theme of the dissertation. This review extensively delves into pivotal aspects encompassing the primary

methodologies employed for hydrogen production. Emphasis is placed on elucidating the intricate technical requisites governing the hydrogen systems, inclusive of the imperative considerations pertaining to materials and the requisite control mechanisms. Moreover, within this chapter, the discussion extends to delineating the advantages intrinsic to hydrogen blending, along with outlining scenarios wherein hydrogen integration proves beneficial.

Chapter 3 entails a comprehensive exposition of the evolution of the GRMS refurbishment project. This journey commences by elucidating the distinctive functional blocks that constitute the system, accompanied by an in-depth exploration of their individual roles. Additionally, the chapter delves into the strategic orchestration of the system's control mechanisms and offers insight into the meticulous material selection process that has been undertaken.

Chapter 4 is dedicated to an exhaustive pipe sizing analysis, meticulously tailored to fulfill both client specifications and regulatory standards. Additionally, a judicious selection of components is undertaken to facilitate the meticulous budgeting of the project.

To conclude, Chapter 5 encapsulates the project's key takeaways and findings. Moreover, it outlines the prospective areas of future endeavor aimed at optimizing this system.

2 State of art

2.1 Overview of natural gas and its production from fossil sources

Natural gas is an abundant and versatile fossil fuel that has been used as an energy source for more than a century. Since its discovery and extraction, it has been a valuable resource for the modern world, being used as a primary source of energy in many areas, such as heating, electricity generation and industry.

This energy resource can be formed by two mechanisms: through thermogenic gas or biogenic gas. Thermogenic gas is formed when layers of buried animals, plants and decomposing microorganisms are subjected to intense pressure for thousands of years, as other layers of earth and rock are superimposed on these, thus increasing the pressure in the layers below.(2, 3) As organic matter is lowered further and further down the earth's crust, temperatures also rise. The combination of these two factors, pressure and temperature, causes the carbon bonds in the organic matter to disintegrate, thus producing thermogenic gas. This gas can be found in underground rock formations or in oil reservoirs. The deeper the reservoir, the higher the pressure and temperature, leading to higher percentages of natural gas compared to oil. This process is responsible for producing most of the commercially exploited natural gas.(3)

As for biogenic gas, it is formed from methanogenic microorganisms. These microorganisms can be found within the intestines of animals as well as in areas of low oxygen near the earth's surface, such as in landfills that are filled with decomposing matter, i.e. methanogenic microorganisms break down into biogenic methane. Although much of this gas escapes into the atmosphere, new technologies are being studied that are capable of containing and harvesting this potential energy source. This process accounts for smaller reserves of natural gas and is so considered a secondary source of production.(3, 4)

2.2 Overview of hydrogen and its production from renewable and fossil sources

Hydrogen is increasingly being used as a clean, renewable energy source because of its environmental benefits and versatility as a fuel. It is the most abundant element in the universe, and can be produced from various sources, such as water, biomass, waste, and natural gas. Its use is gradually replacing natural gas in some sectors, such as industry, transportation and power generation.(5)

One advantage of hydrogen is its versatility as a fuel. It can be used in a wide range of applications, from fuel cell-powered vehicles and trains, to renewable energy storage systems and electric generators. This makes hydrogen a versatile energy source that can be used in many sectors of the economy. However, the production of hydrogen itself requires energy and can result in greenhouse gas emissions, depending on the production method.(5, 6)

There are several methods of hydrogen production with the vast majority coming from fossil fuels (96%) as shown in Figure 1. Within fossil fuels, most of the production, uses as energy source natural gas (48%), followed by oil product with a percentage of 30%.(7)

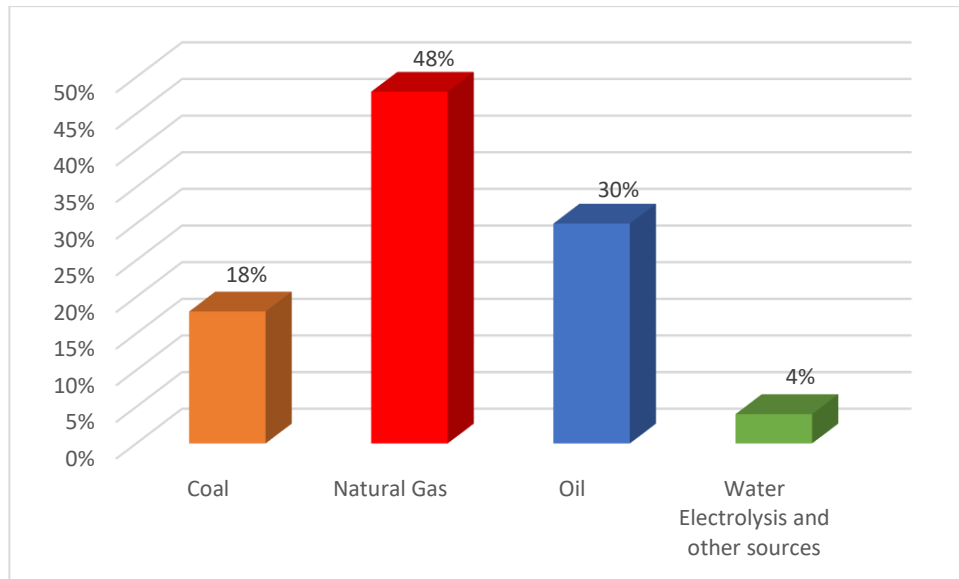


Figure 1- Distribution of the fuels used in hydrogen production (7)

Each of these fuels is used in different hydrogen production processes. Regarding the demanding feedstock and energy source as well as the efficiency of each production process, Figure 2 illustrates possible hydrogen production pathways. In order to identify the source of energy and the path used to produce hydrogen, a color code is used which is also represented in the figure below.(8)

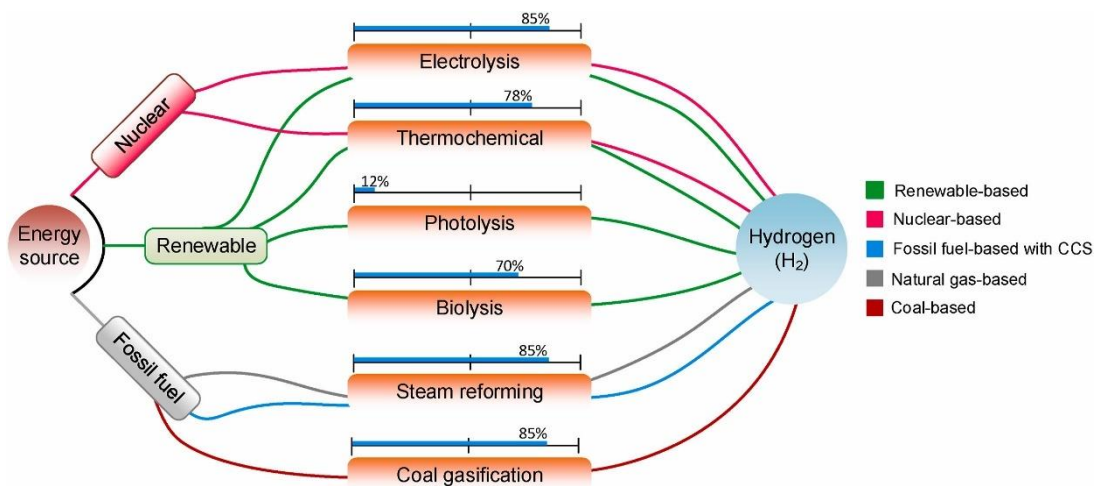


Figure 2- Production pathways of hydrogen (8)

Although there are several processes, there are three colors that are the most common to be used. The colors are blue, green and grey. Using renewable electricity, the water electrolysis process creates green hydrogen. It is referred to as green because there are no CO₂ emissions produced throughout the production process. Water is broken down into hydrogen gas and oxygen by a process called water electrolysis, which employs renewable electricity. In the production of blue hydrogen, fossil fuels are used, but it has the advantage that the CO₂ emitted is captured and stored in an underground reservoir. While gray hydrogen is more polluting because it also uses fossil fuels but the CO₂ is not captured, it is emitted into the atmosphere.(9)

As we can see from the table below, gray hydrogen is the most economical, however, it produces the most greenhouse gas (GHG) emissions, amounting to 11 tCO₂/tH₂. Even being the most polluting is the most used type of hydrogen at the moment, being certain that it will not be a sustainable solution for a long time since there is an increasing concern to control the emission of greenhouse gases. For hydrogen to contribute to the energy transition it must be produced with extremely low or no greenhouse gas emissions, so green hydrogen will be the future. All that is needed is to bring down its production cost, which at the moment is one of the highest.(10)

Grey	Blue	Green
Natural gas	Natural gas	Renewable electricity
Steam methane reforming No CCS	Advanced gas reforming CCS	Electrolysis
High GHG emissions (11 tCO ₂ /tH ₂)	Low GHG emissions (0.2 tCO ₂ /tH ₂)	Potential for zero GHG emissions
1€ - 2.1€ per kg H ₂	1.5€ - 2.9€ per kg H ₂	3€ - 7.5€ per kg H ₂

Figure 3- Specification of the different types of hydrogen (10)

As mentioned before, gray hydrogen is produced from fossil fuels in a process called steam methane reforming (SMR). This process, which is the most widely used today, consists of heating methane, present in natural gas, with the aid of water vapor in order to produce a mixture of carbon monoxide and hydrogen. This reaction is usually carried out in the presence of nickel, which is used as a catalyst.(7, 11)



In a next step, CO will react with water to produce CO₂ and H₂ in a process called water gas shift (WGS). Finally, in order to increase the purity of hydrogen gas, CO₂ is finally extracted from the gas mixture using a CO₂ adsorption device.(11)



H₂ can also be created through the electrolysis of water and the transformation of biomass. Biomass gasification and biological conversion are the two processes that can be used to produce hydrogen from biomass. The biological conversion produces hydrogen using microorganisms such as microalgae and cyanibacteria.(11, 12) Although biomass transformation and water electrolysis are methods for producing hydrogen from sustainable sources, both biomass gasification and biological conversion result in the emission of CO₂ into the atmosphere.(11)

Electrolysis of water was the first method used by humans to obtain synthesized hydrogen. Today, this method is rarely used because it is only applied to small-scale industrial hydrogen

production, amounting to only 4% of global hydrogen production.(5, 13) Despite this, this technology has a good chance of becoming the main method of large-scale hydrogen production in the near future, because it is a process that allows 99.99% pure hydrogen to be produced with almost no GHG emissions. But in order to be able to emit no gases into the atmosphere it is necessary that the electricity used in the electrolysis is from a renewable source, which is yet another hurdle to overcome. There will still need to be a lot of investment in wind and solar farms so that one day we will have enough energy for electrolysis to be viable.(14, 15)

In this way, electrolysis is a cleaner method of producing hydrogen, which involves splitting water molecules into hydrogen and oxygen using an electric current in a device called electrolyzer. Depending on the technique used and the different types of electrolytes, we can classify electrolysis into several types: alkaline electrolysis (AEL), polymer electrolyte membrane (PEM), solid oxide electrolysis (SOEL), and alkaline anion exchange membrane electrolysis (AEM).(16, 17)

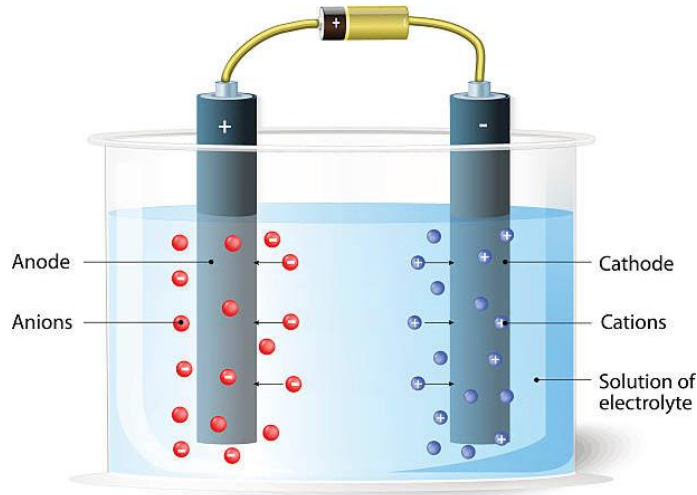
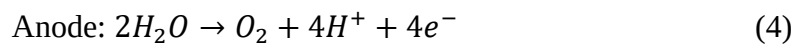
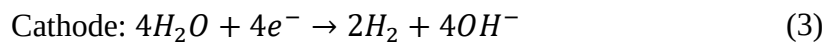


Figure 4- Example of a electrolyzer device(18)

The PEM and AEL methods are the most common processes to be used for commercial purposes and therefore the most mature and developed methods.(11)

In the AEL device, a high concentration alkaline solution, usually KOH or NaOH, is used in which the two electrodes are immersed. Then, when the electric current is passed through the electrolyte, water molecules at the cathode are reduced to hydrogen gas and hydroxide ions (OH^-), while water molecules at the anode are oxidized to oxygen gas and hydrogen ions (H^+). The hydrogen gas produced at the cathode is then collected and can be used as a fuel for various applications, such as fuel cells or for chemical synthesis.(19, 20)



Due to its reduced costs, the AEL approach is more appropriate for application on a commercial scale, however it also has the lowest efficiency (59–70%). In contrast, the PEM method's efficiency levels are between 80 and 90%, but the cost of the components makes it unsustainable (e.g. polymeric membranes).(21)

The PEM cell consists of two electrodes, an anode and a cathode, separated by a thin, proton-permeable membrane. The anode and cathode are typically made of platinum or other noble metals, and are coated with a catalyst that helps to speed up the electrochemical reaction. In terms of the electrochemical reaction, this is the same as the one that occurs in AEL but in this case it occurs in an acidic environment, so it can be said that the two mechanisms are similar. So the major distinction from AEL is that the solid electrolyte is an acidic polymer membrane, and the charge carriers in the electrolyte are hydrogen ions (protons).(11)

2.3 Properties of hydrogen

Hydrogen is a colorless, odorless, and tasteless gas that exists as a diatomic molecule, H_2 , at standard temperature and pressure. It is the most abundant element in the universe and the lightest element, with an atomic number of 1.

One of the most important properties of hydrogen is its high energy content. Hydrogen has a high energy content per unit of mass, making it an attractive fuel for use in various energy applications, such as fuel cells and combustion engines. When hydrogen is combusted with oxygen, it produces water and releases a large amount of energy in the form of heat, which can be used to generate electricity or power vehicles.(22)

Another property of hydrogen that makes it attractive for use in various applications is its low density. Hydrogen has a very low density, which makes it ideal for use in applications where weight reduction is critical, such as in aerospace and automotive industries. Its low density also makes it a valuable fuel for airships and balloons, where it can provide lift without adding significant weight.(23)

However, one of the challenges associated with hydrogen is its high flammability. Hydrogen is highly flammable and can burn with an almost invisible flame, making it a potential safety hazard. However, its flammability also makes it a valuable fuel source, as it can be used to power internal combustion engines or fuel cells.(5)

Another property of hydrogen that makes it useful in various applications is its high thermal conductivity. Hydrogen has a high thermal conductivity, which makes it useful in applications that require efficient heat transfer, such as in cooling systems for electronic devices.

Finally, hydrogen has a low viscosity, which makes it useful in applications that require low friction, such as in lubricants and hydraulic fluids.

In Table 1, we can see some of the values of the properties mentioned above.

Density @ 20°C [kg/m ³]	0.0899
Atomic Mass [g/mol]	1.008
Atomic Radius [nm]	0.078
Energy Density [MJ/Kg]	143
Lower Heat Value [MJ/kg]	118.8
Thermal Conductivity [W/m.K]	0.181699
Viscosity @ 0°C [Pa.s]	8.4×10^{-6}

Table 1- Properties of Hydrogen(24)

In summary, hydrogen has several unique properties that make it a valuable element in a wide range of applications, from energy production and storage to industrial processes and transportation. Its versatility and environmentally friendly nature make it a promising alternative to traditional fossil fuels, particularly in the context of efforts to reduce greenhouse gas emissions and combat climate change.

2.4 Advantages of hydrogen blending

Due to the whole problem of climate and GHG emissions, that the world is currently experiencing, hydrogen blending plays a crucial role. It will be fundamental in the transition process of eliminating fossil fuels. Hydrogen is a clean-burning fuel that produces no greenhouse gas emissions when burned. When blended with natural gas, it can significantly reduce the carbon footprint of the resulting fuel mix. This is particularly important as countries around the world work to reduce their greenhouse gas emissions and meet their climate targets. The benefits of hydrogen blending are numerous, ranging from environmental benefits to improved energy security and technological progress.(25)

Another of the main advantages of hydrogen blending is that there is no need to build a hydrogen transportation network since the hydrogen can be extracted directly where it is required. In this way, we have a more accessible and economical transportation resource.(26)

Improved energy security is another advantage of hydrogen blending. Hydrogen can be produced domestically from a variety of sources, such as renewable energy or natural gas with carbon capture and storage. This reduces dependence on imported natural gas and provides a more secure source of energy for countries that depend on natural gas imports. Especially at a time like this, when with Russia's war with Ukraine, the countries of Europe need solutions to replace the gas coming from Russia.

Hydrogen blending also offers flexibility in its applications. Depending on the blending ratio, it can be used in a variety of applications, such as heating homes and businesses, powering vehicles, and industrial processes. This flexibility makes it a versatile fuel that can be used in different industries, and as a result, it has the potential to drive innovation and technological progress.(27)

Another advantage is that this combination of gases encourages less hydrate development in underwater pipes. Hydrates require methane to form, and since hydrogen has a tiny molecule and methane concentration decreases as hydrogen concentration increases, hydrate formation is prevented. Hydrates provide a significant difficulty because, once produced inside the ducts, they can quickly agglomerate, cause a blockage in the flow of gas, and, in the worst scenario, trigger a duct explosion.(28)

Finally, as more research and development is done in the field of hydrogen production and utilization, the cost of hydrogen blending is expected to decrease, making it more economically viable in the long term. This, combined with its environmental benefits, means that hydrogen blending is likely to play an increasingly important role in the transition to a low-carbon economy.

2.5 Applications of hydrogen

Hydrogen is a highly versatile and abundant element that can be used for a wide range of applications across various industries. One of the most significant applications of hydrogen is in energy production. Hydrogen can be used to generate electricity through fuel cells, which convert the chemical energy of hydrogen and oxygen into electrical energy and water vapor. Fuel cells can be used in stationary power generation, such as in buildings, and in transportation, such as in fuel cell vehicles.

Fuel cell vehicles are one of the most promising applications of hydrogen in transportation. These vehicles use hydrogen fuel cells to produce electricity and power an electric motor, producing only water vapor as a byproduct. Fuel cell vehicles offer several advantages over traditional internal combustion engine vehicles, including zero emissions, greater fuel efficiency, and quieter operation.(29, 30)

Another application of hydrogen in transportation is in the production of hydrogenated liquid fuels. These fuels, such as methanol and ammonia, can be produced using hydrogen and carbon dioxide and can be used in internal combustion engines or fuel cell vehicles. Hydrogenated liquid fuels offer several advantages over traditional fossil fuels, including lower greenhouse gas emissions and the potential for carbon recycling.(31, 32)

Hydrogen can also be used as a fuel source for heating and cooling buildings. Fuel cell systems can provide both electricity and heat, while hydrogen-powered air conditioning systems can provide cooling without the use of harmful refrigerants. These systems offer a more efficient and sustainable alternative to traditional heating and cooling methods.(33)

In addition to energy production and transportation, hydrogen is used in a variety of industrial applications. One of the most significant applications is in the production of ammonia for fertilizer. Hydrogen is combined with nitrogen to produce ammonia, which is a key component of many fertilizers. Hydrogen is also used in the refining of petroleum and in the production of steel.(34)

Hydrogen can also be used as a means of storing energy. Excess energy from renewable sources like wind and solar power can be used to produce hydrogen through electrolysis, which can then be stored and used later to generate electricity. This method of energy storage has the potential to play a critical role in the development of a more sustainable energy system, as it can help balance the intermittent output of renewable sources.(35)

Overall, hydrogen has a wide range of potential applications that could help reduce greenhouse gas emissions and move toward a more sustainable future. However, widespread adoption of hydrogen technologies will require significant investment in infrastructure and research and development to overcome technical and economic challenges. Despite these challenges, the versatility and abundance of hydrogen make it a promising candidate for addressing some of the most pressing environmental and energy-related issues of our time.

2.6 Distribution networks

In order to be able to proceed with the mixing of hydrogen with natural gas, it is necessary to study the different ways of transporting it. Three different methods of distribution are possible: 100% hydrogen pipeline transportation, vehicle transportation, and hydrogen gas combination with methane that is carried through already-existing gas pipes. For this it is necessary to analyze the infrastructures that already exist and how they can be used for this purpose.

2.6.1 National natural gas network

Since 1996, with the inauguration of the Maghreb-Europe gas pipeline, until 2021 Portugal received most of its natural gas through Spain. This pipeline transported natural gas from Algeria to Spain, and then through other pipelines this gas was transported to Portugal. But in 2021, due to political and geostrategic reasons, this pipeline was forced to be closed. Because the gas sent by Algeria, which was transported by this pipeline to Spain, crossed the territory of Morocco and, as these two countries cut relations, the closure of this pipeline was forced. Due to this incident, Algeria was forced to find another solution to export its gas to the Iberian Peninsula and the solution it found was to bring the gas into the sea from Portugal through the port of Sines.(36)

In the present days, the natural gas network in Portugal has 3 entry/exits, the main entry point which is the port of Sines, the main exit point which is in Campo Maior that serves to supply Spain and an entry/exit in Valença where there is only a residual flow, not being this way a point of great importance, this only exists more in case of emergency.

Within the national territory there are 3 types of pipelines: gathering lines, transmission lines and distribution lines.

- **Gathering lines:** is a network of high-pressure pipelines (over 20 bar) responsible for transporting large volumes of natural gas over long distances, from the production plants or natural gas entry points (such as the Sines LNG terminal) to the GRMS. At these stations, natural gas is reduced to medium pressure and its filtered to remove any impurities, and then distributed to the medium and low pressure natural gas distribution networks. The management of these infrastructures in Portugal is carried out by REN - Redes Energéticas Nacionais.
- **Transmission lines:** is a network of medium-pressure pipelines (between 20 and 4 bar) that distribute natural gas from the regulating and metering stations to the delivery points, such as businesses, industries, and large consumers. These pipelines are typically smaller in diameter than high-pressure pipelines and can be buried in the ground or placed on overhead supports.
- **Distribution lines:** These are pipelines that distribute natural gas at low pressure (below 4 bar) from the delivery points to the final consumers, such as homes, small businesses, and restaurants. These pipelines have smaller diameters and are usually buried in the ground or placed on overhead supports.(37)

Between the gathering and transmission lines there is an odorization system installed, because as methane is an odorless and extremely inflammable gas it is mandatory for safety reasons that it has an odor so that in case of leakage it is more easily detected. In Portugal the gas that is injected to give the smell is tetrahydrothiophene.

In the Figure 5 we can see all the network pipelines of Portugal.



Figure 5- National natural gas network(38)

2.6.2 Transport of hydrogen

With regard to hydrogen transportation there are two options: the first is to use the existing infrastructure in Portugal, currently used for natural gas transportation, the second is to build a whole new network of hydrogen pipelines and the third is to transport hydrogen via vehicles.

When it comes to transporting hydrogen through natural gas pipelines, this solution is technically possible, but requires some adaptations in the existing infrastructure. This is because hydrogen has different properties than natural gas, which can affect the performance and safety of the pipeline network.

One of the main issues that needs to be considered is that hydrogen is a lighter and more reactive gas than natural gas, which can affect the integrity of pipelines and connections. In addition, hydrogen can leak more easily than natural gas, which can increase the risk of leaks and therefore of explosions and fires. For this reason, it is necessary that the natural gas transportation infrastructure be adapted to transport hydrogen, using appropriate materials and implementing specific safety measures. Some companies and countries are already conducting studies and pilot tests to evaluate the technical and economic feasibility of transporting hydrogen through natural gas pipelines. One of the solutions has been to transport a mixture of natural gas and hydrogen (with percentages of hydrogen up to about 20%) because in this way the transformation in the pipeline network is more gradual. The goal is to be able to completely replace natural gas with hydrogen.

As for the possibility of building a whole new network of pipelines for the transportation of hydrogen, for the time being this is not a very viable solution because it would imply an unbearable investment for the time being.(39, 40)

As for the third hypothesis, which is the transportation of hydrogen via tanker trucks, it is the most widely used, but also the most environmentally damaging. This fact is due to the use of diesel as fuel, which emits greenhouse gases. Which makes this solution not a long-term solution, not an option for the future. One solution to this problem would be to use vehicles powered by green energy.(41)

2.7 Storage of hydrogen

Storage of hydrogen is a critical aspect of its development as a fuel source. Hydrogen is a gas at ambient temperature and pressure, and one of the main challenges with hydrogen is its low density, which makes it difficult to store in its gaseous form. Therefore, researchers and engineers have been developing various methods for storing hydrogen in a compact and safe form.

Currently there are a few storage methods that will be discussed next. Within the different methods we can separate them into two groups, the physical methods and the chemical methods. Starting with the physical methods here are some of the main examples:

2.7.1 Compressed hydrogen gas

Compressed hydrogen gas storage is one of the most common methods for hydrogen storage. In this method, hydrogen gas is compressed to high pressures, typically between 350 and 700 bar, which significantly reduces the volume of the gas and increases its energy density. The compressed hydrogen gas is stored in strong and heavy tanks that are designed to withstand the high pressure and prevent any leaks.

The advantages of compressed hydrogen gas storage include its simplicity, low cost, and relatively high energy density. This method of storage is widely used in stationary hydrogen storage systems, such as for industrial processes or fuel cells, and can also be used in vehicles that run on hydrogen fuel cells.

However, there are also some disadvantages and challenges associated with compressed hydrogen gas storage. First and foremost, the high pressure involved in compressed hydrogen gas storage can pose safety risks, and the tanks used for storage need to be designed and manufactured to strict safety standards. Additionally, the heavy and bulky tanks required for compressed hydrogen storage can make the system less portable and limit the range of hydrogen fuel cell vehicles.(42, 43)

2.7.2 Liquid hydrogen

Liquid hydrogen storage is another method for storing hydrogen. In this method, hydrogen gas is cooled down to a very low temperature of -253°C (-423.4°F) to condense it into a liquid state. The liquid hydrogen is then stored in insulated tanks to prevent heat from entering and causing it to evaporate.

One of the main advantages of liquid hydrogen storage is that it has a higher energy density compared to compressed hydrogen gas storage. Liquid hydrogen has a much higher density than hydrogen gas, so more hydrogen can be stored in the same volume. This makes liquid hydrogen a more practical option for applications that require high energy density, such as long-range hydrogen fuel cell vehicles.

However, liquid hydrogen storage also has some disadvantages and challenges. One of the main challenges is the requirement for cryogenic cooling systems to maintain the extremely low temperature needed to keep the hydrogen in a liquid state. This makes the infrastructure for liquid hydrogen storage more complex and expensive compared to compressed gas storage. Additionally, liquid hydrogen storage tanks need to be very well insulated to minimize heat transfer, which adds to the overall weight and cost of the storage system.

Another challenge associated with liquid hydrogen storage is safety. Liquid hydrogen is extremely cold and can cause frostbite or burns if it comes into contact with skin. Additionally, liquid hydrogen can cause fires or explosions if it leaks and comes into contact with an ignition source.(43, 44)

Regarding the chemical methods, the main methods are also presented below:

2.7.3 Adsorption

Adsorption is a method for hydrogen storage that involves absorbing hydrogen gas onto a solid material, such as activated carbon or metal-organic frameworks, which have high surface areas and can bind to hydrogen molecules.

In this method, the solid material is typically packed into a container, and hydrogen gas is then passed through the container, where it is adsorbed onto the material. The container can be designed to allow the hydrogen to be released on demand, by heating or depressurizing the material to break the bond between the hydrogen and the material.

One of the main advantages of adsorption as a method for hydrogen storage is that it can offer a high storage capacity with a low weight and volume. Adsorbent materials can store large amounts of hydrogen in a compact space, making them suitable for portable applications, such as hydrogen-powered vehicles. Additionally, adsorption does not require cryogenic cooling or high-pressure tanks, which can simplify the storage system and reduce infrastructure costs.

However, there are also some challenges associated with adsorption as a method for hydrogen storage. One challenge is the slow kinetics of hydrogen adsorption and desorption, which can limit the rate at which hydrogen can be stored and released. This can be addressed by using materials with high adsorption and desorption rates or by optimizing the conditions of the adsorption process.

Another challenge is the stability and durability of the adsorbent material, which can be degraded over time by repeated adsorption and desorption cycles or exposure to harsh operating conditions. Researchers are developing new materials with improved stability and durability to address this challenge.(43)

2.7.4 Metal hydrides

Metal hydrides are a class of materials that have the ability to store hydrogen through the formation of chemical bonds between the hydrogen molecules and the metal atoms. This process is reversible and can be used to release hydrogen when needed.

In the metal hydride storage method, hydrogen gas is first absorbed by the metal hydride under certain conditions of pressure and temperature. The absorption process involves the dissociation of hydrogen molecules into individual hydrogen atoms, which are then adsorbed by the metal atoms to form metal hydrides. This process occurs at a relatively low temperature and pressure compared to other storage methods such as compression.

The hydrogen can then be released from the metal hydride by heating it to a certain temperature or by reducing the pressure. When heated, the metal hydride breaks down into its constituent metal and hydrogen gas, which can then be used as a fuel source.

Metal hydrides have several advantages over other storage methods, including a high storage capacity, low pressure and temperature requirements, and ease of handling. They also have a high degree of safety since hydrogen is stored in a chemically bound form, which reduces the risk of explosion or fire.

However, metal hydride storage also has some limitations. One major drawback is that the absorption and desorption processes can be slow, limiting the rate at which hydrogen can be stored or released. Additionally, the cost and availability of some metals used in metal hydride storage can be a limiting factor for large-scale commercial applications.

Despite these challenges, metal hydride storage remains an important area of research and development for hydrogen storage, and new materials and methods continue to be explored in order to improve the efficiency and viability of this storage method.(45, 46)

2.7.5 Absorption on interstitial sites

Absorption on interstitial sites in a host metal at ambient pressure and temperature is a method for hydrogen storage that involves absorbing hydrogen atoms into the interstitial sites of a host metal lattice structure, such as palladium or nickel. Interstitial sites are the spaces between metal atoms in the crystal lattice structure of the host metal, and hydrogen atoms can be absorbed into these sites without significantly disrupting the lattice structure.

In this method, the host metal is typically in the form of a thin film or powder with a high surface area, which allows for a larger number of interstitial sites to be available for hydrogen absorption. The absorption of hydrogen atoms onto the interstitial sites occurs through a process called adsorption, which is a surface phenomenon where gas molecules adhere to the surface of a solid material.

One of the advantages of the absorption on interstitial sites method is that it can offer high storage capacity with low weight and volume. Additionally, this method operates at ambient pressure and temperature, which simplifies the storage system and reduces infrastructure costs.

However, there are also some challenges associated with this method. One challenge is that the kinetics of hydrogen absorption and desorption can be slow, which can limit the rate at which hydrogen can be stored and released. This can be addressed by optimizing the surface area of the host metal and the conditions of the adsorption process, such as temperature and pressure.

Another challenge is the durability and stability of the host metal. Repeated absorption and desorption cycles can cause the host metal lattice structure to degrade over time, reducing its ability to absorb and release hydrogen. Researchers are working to develop new host metal materials with improved durability and stability to address this challenge.(47)

2.8 Limitations of using hydrogen in the gas natural network

2.8.1 Material problems and safety concerns

The use of hydrogen in the natural gas network presents material problems and safety concerns that need to be addressed before it can be widely adopted. One of the primary material problems is the compatibility of existing infrastructure, including pipelines, compressors, and storage tanks. The materials used in these structures, such as steel and polymers, may not be compatible with high-pressure hydrogen. When some metals and alloys are exposed to hydrogen gas, a phenomenon known as hydrogen embrittlement takes place. The ductility and strength of these materials can be reduced as a result of this phenomenon, increasing the risk of catastrophic failure, which can be a serious problem. Therefore, the pipeline infrastructure may require replacement or significant modifications to handle hydrogen.(48)

Non-destructive testing techniques are one method that has been developed to better understand hydrogen embrittlement. These techniques enable evaluation of hydrogen content and presence in a material without causing degradation to the component. A range of materials and applications can be evaluated for the possibility of hydrogen embrittlement using techniques such as magnetic particle inspections, ultrasonic, eddy current, acoustic emission, liquid penetration tests, and radiography.

One of the main challenges is the difficulty in detecting hydrogen embrittlement. The presence of hydrogen in a material does not necessarily lead to embrittlement, and its effects may not be visible until a failure occurs. Additionally, the conditions that cause hydrogen embrittlement can be challenging to reproduce in a lab context, making it challenging to forecast how a material would behave in a real-world setting.(49)

To mitigate these safety concerns, proper handling, storage, and transport of hydrogen are essential. This includes proper ventilation in storage areas, monitoring of hydrogen concentrations in the air, and use of specialized equipment designed for handling hydrogen. Additionally, safety measures such as pressure relief valves and flame arrestors can help prevent explosions and fires.

2.8.2 Combustion concerns

When injecting hydrogen into the natural gas network, there are several factors to pay attention to because these can lead to cases of excess pressure in the pipeline that can result in explosions and rupture in the infrastructure. The study by Lowesmith et al. (50) shows that concentrations up to 30% do not cause significant changes with regard to maximum overpressure. However, when a concentration of 40% was exceeded, this risk increased dramatically.

Because hydrogen is being used as a fuel more frequently and because it has several distinct properties that can pose problems for its combustion and flame behavior, the combustion and flame behavior of hydrogen are also a crucial topic of research for many different sectors.(51)

When it comes to the hydrogen flame, there is one danger that stands out. While the natural gas flame is visible to the human eye, the hydrogen flame is virtually undetectable by our eyes. This makes hydrogen combustion much more dangerous for safety reasons, since in the event of leaks and ignition it is more difficult to detect.

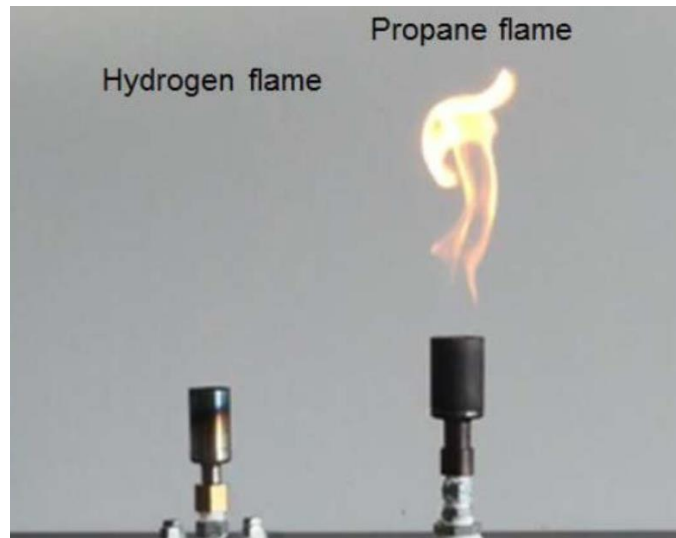


Figure 6- Flame image of hydrogen (left) and propane (right)(52)

As far as flame speed is concerned, hydrogen's is very high. There are currently several studies demonstrating this, where it is possible to compare the flame speed of hydrogen with that of natural gas. In the study by Don et al. (53) the laminar flame speed of mixtures of H₂/air and NG/air is compared, and it was concluded that for the same equivalence ratio the hydrogen flame speed can be up to 52 times higher than that of natural gas. This is verified for an equivalence ratio of 1.7, where hydrogen has a laminar flame speed of 2.6 m/s while that of natural gas is only 0.05 m/s. Although this difference is not the same for all equivalence ratios, it is possible to see how much higher the laminar flame speed of hydrogen is. We can prove these values in Figures 7 and 8.

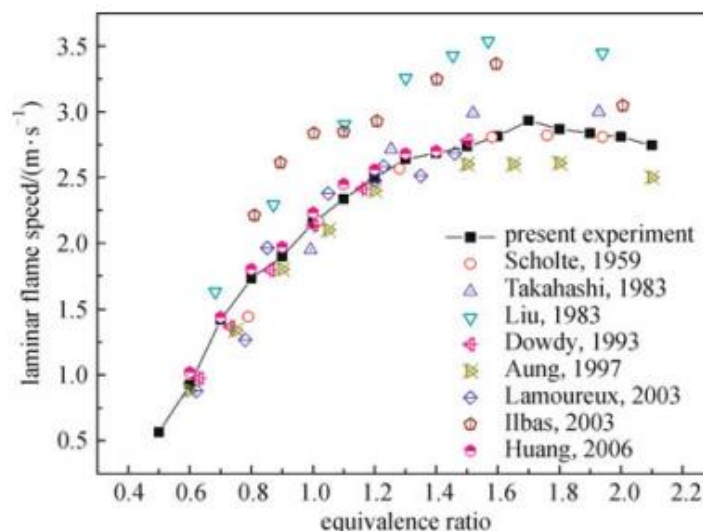


Figure 7- Laminar flame speed of H₂/air versus equivalence ratio(53)

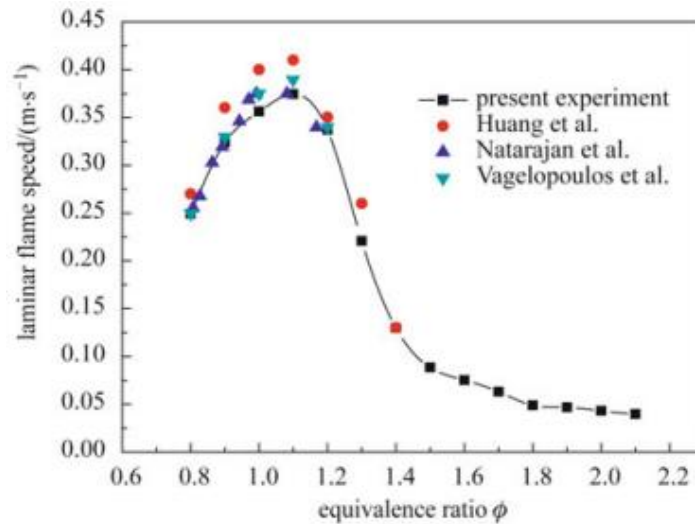


Figure 8- Laminar flame speed of NG/air versus equivalence ratio(53)

Another problem is the sensitivity of hydrogen flame behavior to the presence of contaminants. Even small levels of contaminants, like dust or water vapor, can drastically alter the behavior of hydrogen's flame, causing undesirable instabilities or flashbacks. Hydrogen should be an exceedingly clean fuel.

Applying flame retardants is one method for regulating hydrogen's unintended combustion and flame behavior. To lessen the chance of igniting, these compounds can be directly added to hydrogen fuel or put on the surface of items that come into contact with hydrogen. By putting a barrier between the fuel and the oxygen, flame retardants act as combustion inhibitors.

In overall, it's critical to address the risks connected to hydrogen combustion in a proactive manner. These techniques can be used to successfully lower the danger of unwelcome flames and explosions.(54)

3 Development of a gas regulation and measurement station (GRMS)

This chapter aims to study the feasibility of modifying the Valongo GRMS to allow its utilization with a mixture of natural gas and hydrogen. Each section of the station will be thoroughly analyzed, considering operational aspects. The central idea is to investigate how this infrastructure can be adapted to accommodate the proper injection and distribution of this new gas mixture.

In the following chapter will be detailed each section of the GRMS, from the gas inlet, through the filtration processes, the pre-heating module, pressure reduction and metering, to the delivery of the final product to consumers.

This study aims contribute to the advancement of hydrogen integration in the energy network, bringing new perspectives to the natural gas sector and encouraging the adoption of more sustainable solutions.

3.1 Functional blocks

In the following subchapters, each section of the GRMS will be discussed, explaining its operation and presenting the corresponding P&ID. To carry out this P&ID, it was initially considered which components were mandatory for the correct operation of the system and then thought about the valves that would need to be used to be able to control the system as intended. This project enabled the development of the P&ID which is attached in Appendix A.

To better understand the P&ID it is important to note that in the GRMS there are two filtration modules, two preheating modules, two pressure regulation modules and three metering modules. This is so that in the event of a failure, there is always the possibility of redirecting the flow to one of the other modules and thus be able to fix the failures without the station stopping working. In the case of the metering module there are 3 lines that can be used and not two as in the other modules. This is for economic reasons, as it is financially worthwhile to use two lines simultaneously instead of one, as it is possible to use pipes and turbine meters of smaller diameters since the flow is divided. The third line exists for the same reason as the other modules so that it can be used in the event of a failure of one of the other lines.

3.1.1 Input Module

The inlet module is the first part of the station where the gas arrives from the transmission line. It is essential to check the temperature and pressure of the gas coming from the pipelines to ensure that it can enter the station in compliance with all safety requirements.

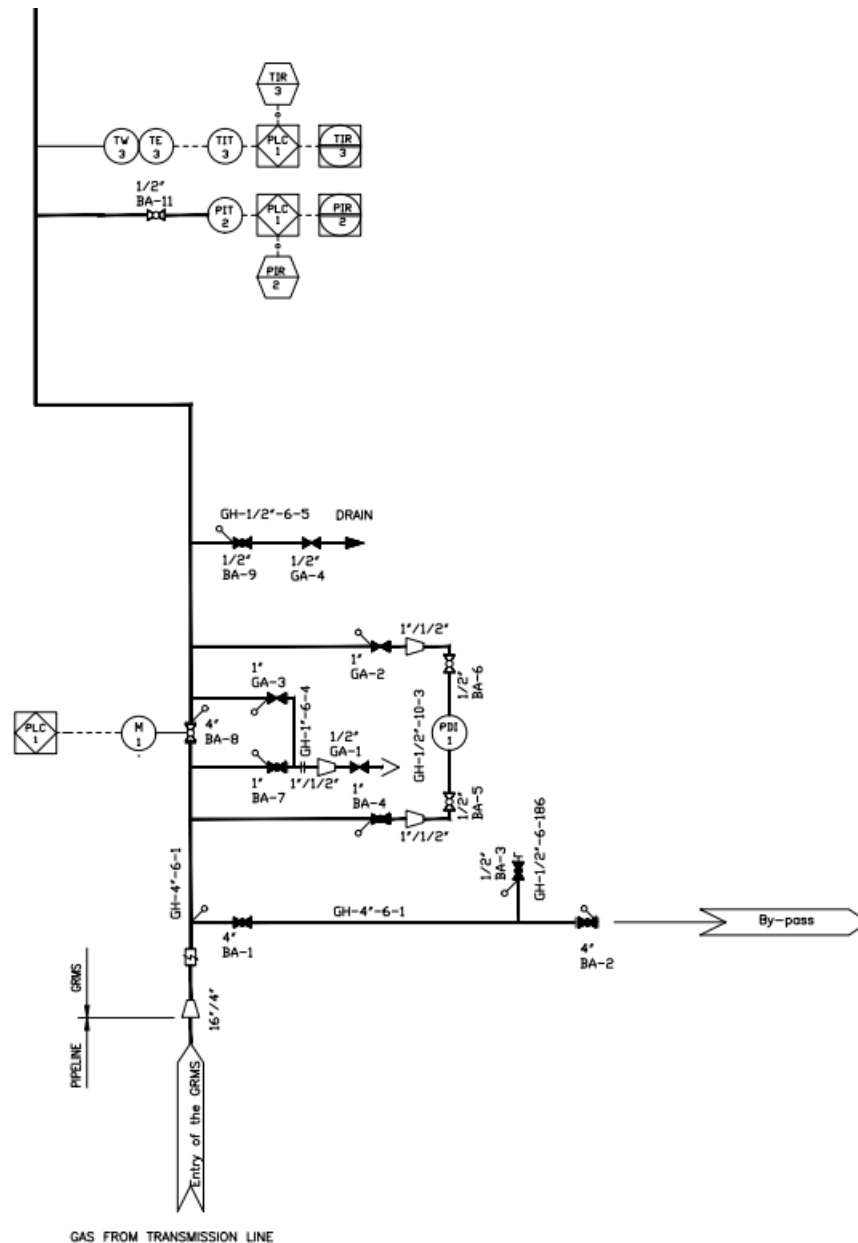


Figure 9- Input Module

In Figure 9, it's possible to see how this block will be constituted. The first component of this module is an insulating coupling which is extremely important for the station. The main function of this component is to provide electrical isolation between the input pipeline and the rest of the equipment inside the station. This is especially important in cases where electrical potential differences may exist between the pipeline and the station's electrical systems, which may result from various factors such as ground potential differences, lightning strikes or other electrical events that may lead to hazardous conditions. This component may also help prevent galvanic corrosion if the pipeline material is different from the station pipe material.

Then there is a connection to a by-pass that is not built, it only has the elements so that later if necessary it will be easier to build it. This by-pass is used to connect the station entrance to the station exit. It can be useful if you want to make a direct connection so that the gas does not pass through the station in case the station becomes unusable.

There is a motorized ball valve that has a pressure differential indicator (PDI) connected downstream and upstream that allows the assessment of whether this valve can open safely and

sends a signal to the PLC that will control the valve. Since the gas arrives at the station at a high pressure, if the pressure differential is too great it can cause major damage to the pipes, hence the importance of this PDI. This valve also has a by-pass to balance the pressures downstream and upstream of the valve if the pressure differential is too great. This by-pass also has the possibility to depressurize the pipelines through a vent.

When the gas starts to flow through the ball valve, it goes through a pressure and temperature check. In this way, if any of the pressure or temperature values are out of the desired range, it is possible for the PLC to read this change and switch the motorized ball valve and shut down the system. A temperature indicator transmitter (TIT) and a pressure indicator transmitter (PIT) are used for this purpose.

Both temperature element (TE) and temperature indicator (TI) are coupled with a thermowell (TW) that is an equipment used as a protective sleeve that encases the thermometer providing a measure of protection against damage from the gas flow. This component also allows the thermometer to be safely removed for maintenance or replacement without interrupting the process flow.

3.1.2 Filtration Module

The filtration module is fundamental in the installation since it filters all solid impurities that mixture may contain. These impurities may be present in the flow, for example due to wear in the pipes and they can be harmful to the components present in the GRMS.

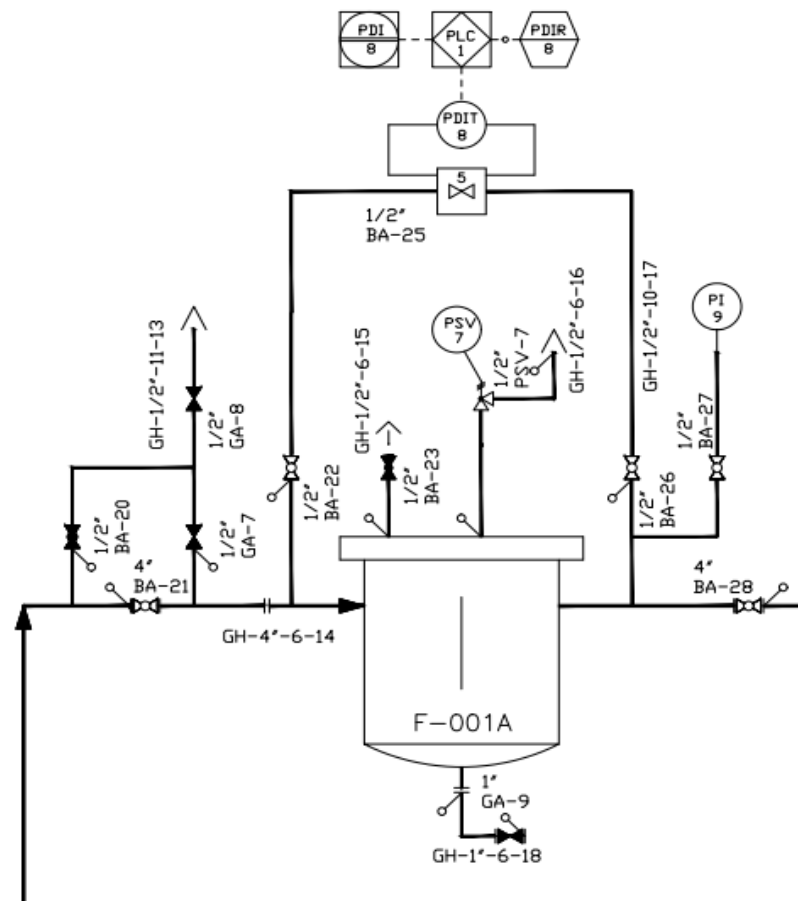


Figure 10- Filtration Module

In Figure 10, it's possible to see how this module will be constituted. There are two ball valves one at the beginning and one at the end of this module which allows to close this filter line in case of failure or if it necessary to change the filter or to divert the flow to the alternative filter line. The first ball valve has a by-pass and a vent as in the inlet module which is used for the same reasons.

The filter has one pressure tap before and one after so that, once connected to a pressure differential indicating transmitter (PDIT), it will be possible to see the state of the filter (if it is clean or not). The filter has a gate valve at the bottom that allows condensate that may form inside to drain. In addition, it has a pressure safety relief valve that is mandatory in filters so that if, for some reason, the filter clogs and the pressure starts to increase, reaching a certain pressure the valve opens and relieves the pressure in the filter. There is also a ball valve attached to the filter which allows the gas to be removed if any intervention is required.

3.1.3 Pre-heating Module

The main function of the preheating module is to heat the mixture of natural gas and hydrogen before its pressure is reduced, because by reducing the pressure, due to the joule-thomson coefficient, its temperature will decrease too. And with this there may be a danger of the fluid changing physical state or going to temperatures that are not the most suitable for the correct operation of the station.

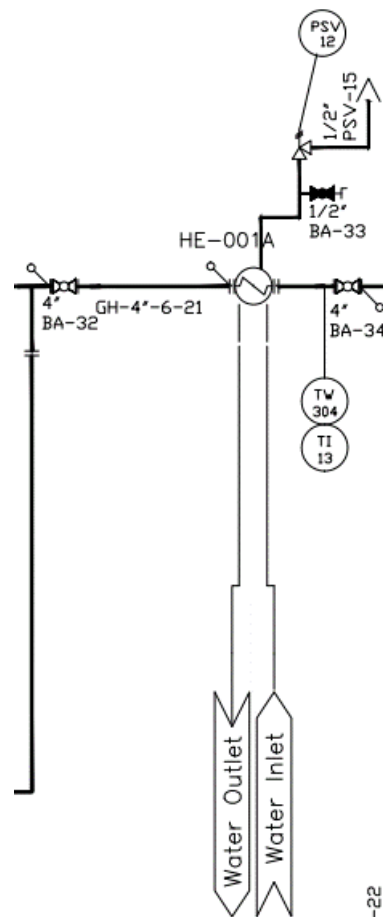


Figure 11- Pre Heating Module

As can be seen in Figure 11, once again there are two ball valves, one at the beginning and one at the end of the module, which work exactly as explained in the previous modules, to be able to divert the flow to the secondary line in case it is necessary to carry out some type of maintenance on this module.

Next, the gas will enter a heat exchanger, where hot water circulating through pipes will transfer heat to it until it reaches the desired temperature. In the heat exchanger there is a pressure safety relief, which according to the standards is mandatory for safety reasons, because if for some reason the pressure reaches values considered dangerous it will open and depressurize to balance the pressure.

Finally, we have a temperature indicator (TI) coupled with a thermowell (TW) so that it is possible to take a direct reading of the gas temperature value at the outlet of the heat exchanger.

3.1.4 Pressure Regulating Module

At this stage, with the fluid already heated, the pressure can be regulated so that it can continue to the distribution system until it reaches the customers with a safe pressure. In order to make this regulation possible, the following module was built as shown in Figure 12.

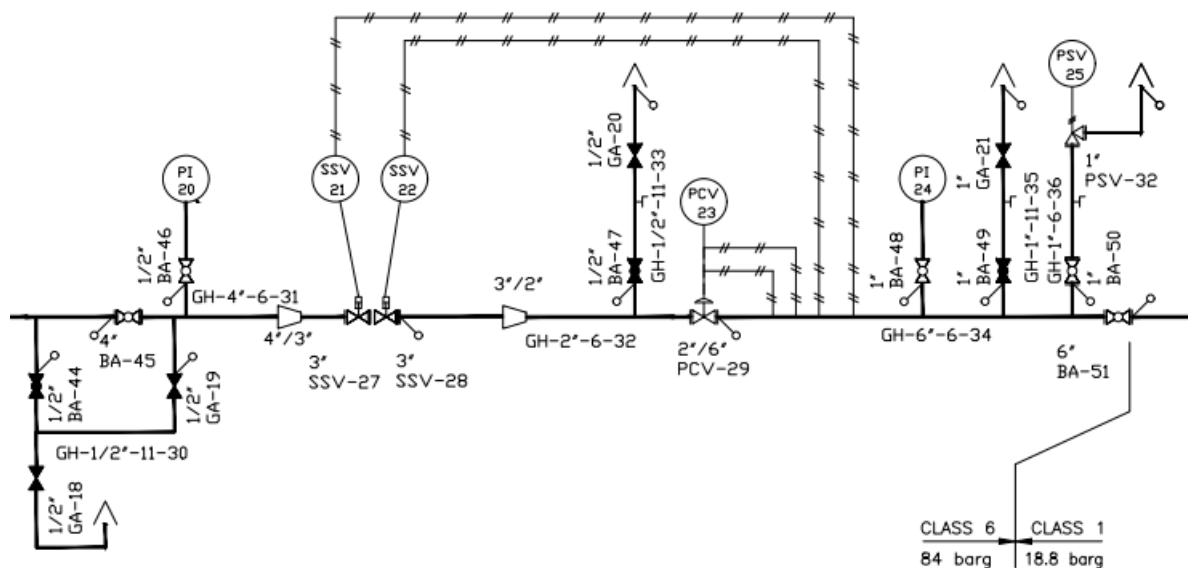


Figure 12- Pressure Regulating Module

The pressure reduction is done at the pressure control valve (PCV) which will bring the fluid to the preset pressure so that it can proceed to the distribution system. If there is any failure with this valve, we have two slam shut valves that are placed upstream of the PCV and are connected downstream of the PCV with a pneumatic system. This pneumatic system allows these valves to evaluate the pressure downstream of the PCV and if, due to some failure, the pressure is too high, they will automatically switch, thus closing the circuit. The existence of two equal valves in a row is due to the safety standards that require it.

It is possible to see the existence of two PI so that the pressure can be checked before and after the PCV, as well as a PSV that will depressurize the pipeline if there is the failure mentioned above and the SSVs are activated.

3.1.5 Metering Module

In a final step, the gas goes to the metering module. At this stage, the volume flow rate passing through the turbine is measured. It is customary to measure the volumetric flow and not the mass flow because Coriolis meters (mass meters) have many disadvantages such as their high price, higher pressure losses and higher maintenance requirements.

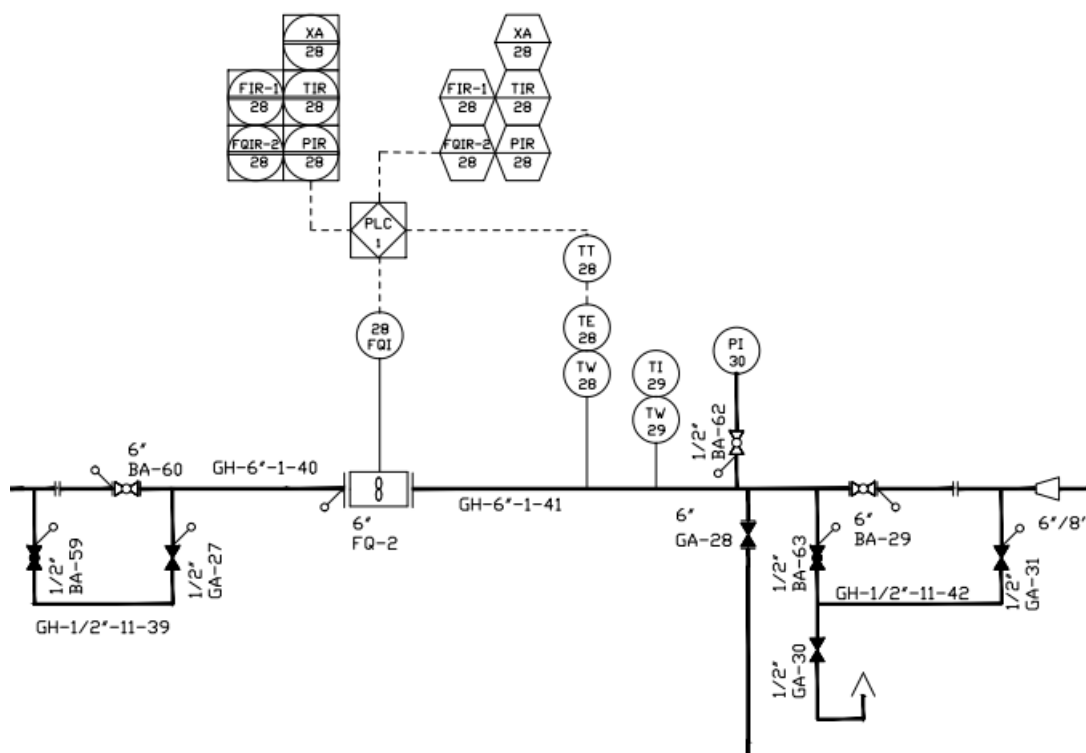


Figure 13- Metering module

In Figure 13, it's possible to see the metering module, again with the two ball valves at the beginning and end of the module as well as the by-passes. The gas then passes through a metering turbine which is connected to a PLC that will record the real time flow (FIR) as well as the total amount of fluid that has passed (FQIR). In case of an anomalous amount of flow an alarm will be activated (XA). Temperature is also measured to ensure that the fluid is in the desired range.

A Z-shaped configuration, Figure 14, was built to connect the three meter lines in order to facilitate maintenance and control of the meter turbines. In this way, it is possible to calibrate the metering turbine of the second line and by passing the flow through the first line and then through the second line compare the measured flow values. If the value measured by the second line is equal to that of the first line, it's possible to say that the metering turbine of the first line is also calibrated. The same can be done with the third line, always taking as a reference value the flow measured in the second line. This makes maintenance much more efficient.

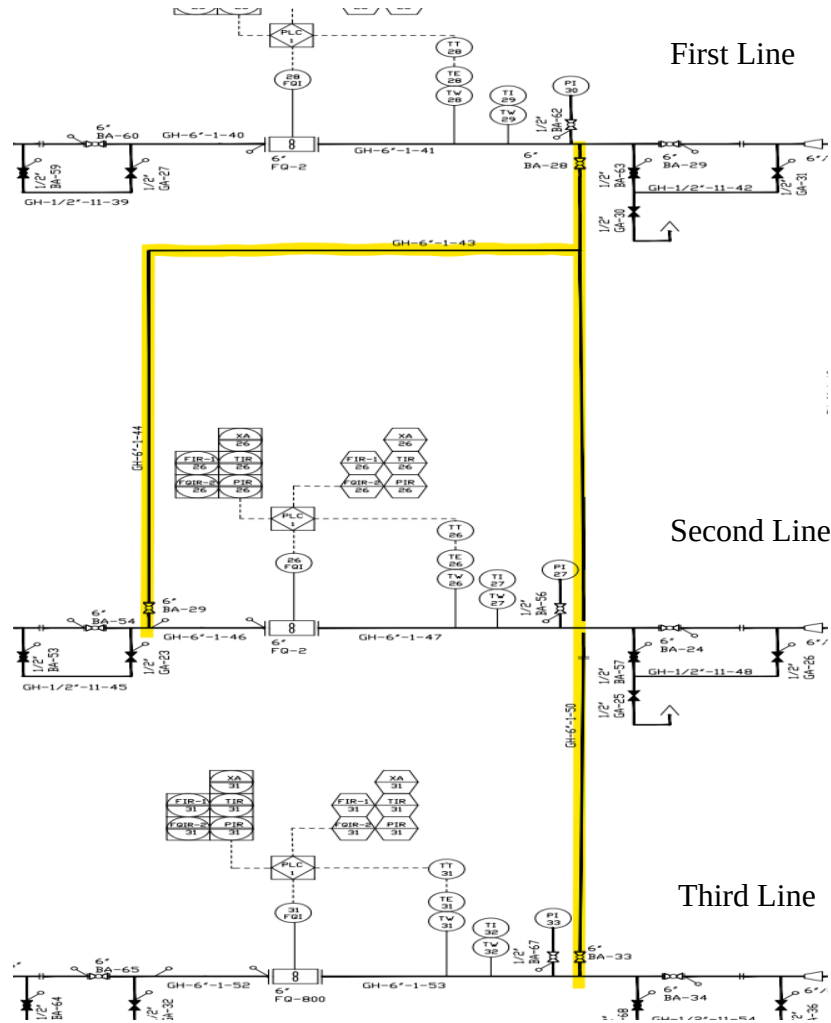


Figure 14- Z - Shaped configuration

3.1.6 Output Module

Finally, the output module, where various parameters such as temperature and pressure will be evaluated to ensure that there are conditions for the fluid to go to the distribution system. Firstly, the temperature of the flow is measured, and through a temperature transmitter (TT) a signal is sent to the heating system (boiler) to make the adjustment if it is necessary to heat or cool the water used in the preheating module. The pressure sensor also has a transmitter (PIT) that sends a signal to the PLC.

Lastly, as with the input module, there is a motorized ball valve with a PDI connected to it with the same function as the input module. This system can be seen in Figure 15.

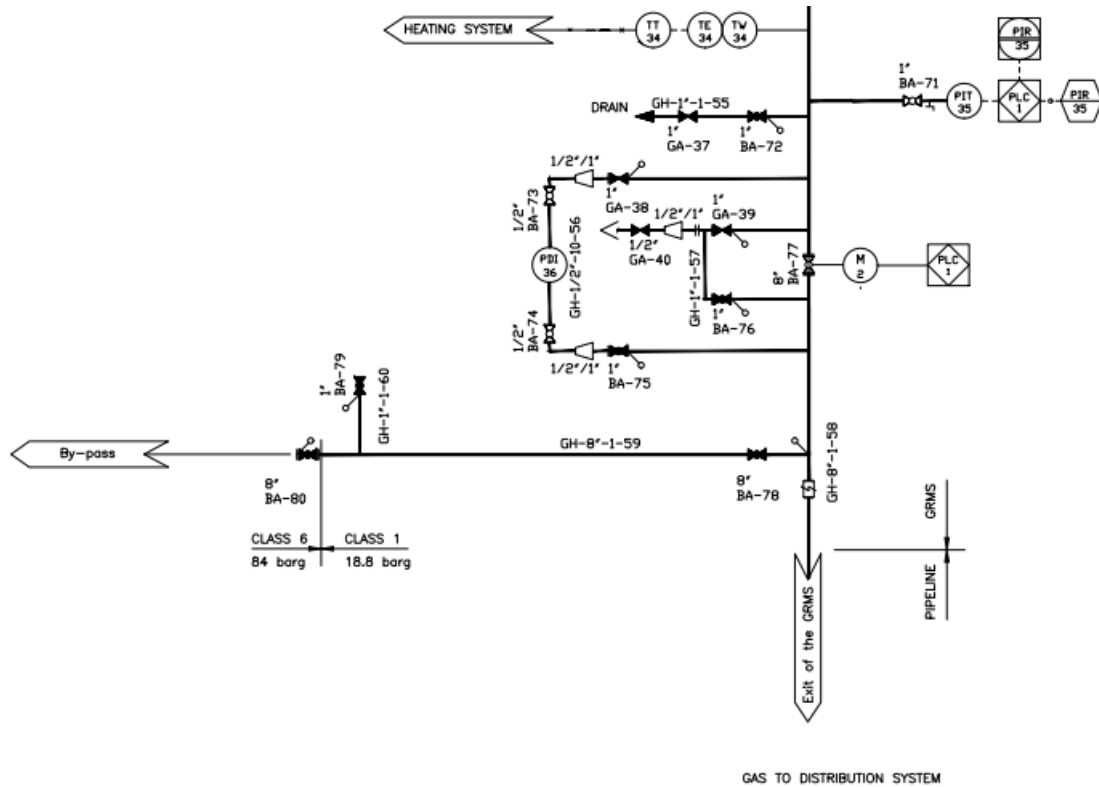


Figure 15- Output Module

3.2 Pipe Material Selection for GRMS

In the pursuit of establishing a secure and efficient hydrogen transportation system, the meticulous selection of appropriate pipe materials stands as a pivotal decision. When delving into the realm of hydrogen pipe material selection, a multitude of critical factors come into play. Among these considerations, the prevailing pressure and temperature conditions take precedence, wielding a significant influence on the overall material performance. Furthermore, the specter of hydrogen embrittlement looms large, necessitating careful assessment to avert the brittleness and potential failure of chosen materials. The economic viability and material availability must also be factored into the equation.

There are several options in the arsenal of materials suitable for hydrogen and natural gas transport pipes. Carbon steel emerges as a robust and economical candidate, although it is susceptible to the dangers of hydrogen embrittlement. In contrast, stainless steel, commanding corrosion resistance and immunity to hydrogen embrittlement, presents itself as a more premium alternative, albeit at a higher cost. The lightweight and corrosion-resistant attributes of aluminum render it a compelling contender, though its feasibility for high-pressure applications may warrant scrutiny. Copper boasts commendable conductivity and corrosion resistance, tempered by its higher cost and potential limitations under elevated pressures. Plastic and composite materials enter the fray with their weightlessness and corrosion resilience, yet their suitability for high-pressure scenarios remains a concern. Each material species carries its distinct advantages and drawbacks, with the optimal choice pivoting upon the distinctive exigencies of the system. By meticulously considering these aspects, a judicious decision can be made to orchestrate the safe and efficient transport of the natural gas-hydrogen mixture.

Given the specific pressure and temperature parameters of 72 bar and 10°C, stainless steel emerges as a highly promising candidate for hydrogen pipelines. Its capability to endure

elevated pressure circumstances, coupled with its immunity to both corrosion and hydrogen embrittlement, positions it as a superior choice. Furthermore, stainless steel presents an attractive economic proposition, rendering it a compelling option for hydrogen conveyance purposes.

An alternative consideration could involve carbon steel, which boasts strength and cost-effectiveness. Nevertheless, it is essential to acknowledge its heightened vulnerability to hydrogen embrittlement when compared to stainless steel. This factor introduces potential long-term reliability concerns.

Aluminum and copper could be assessed as well, particularly for their potential suitability under high temperature and pressure conditions. However, it is worth noting that these alternatives may incur greater costs and might not exhibit the same level of resistance against corrosion and hydrogen embrittlement that stainless steel offers.

To summarize, the chosen material for hydrogen pipelines is stainless steel. This selection derives from its balanced attributes, encompassing robust strength, commendable resistance against corrosion and hydrogen embrittlement, economical viability, and capacity to withstand the rigorous demands posed by the system's operating conditions.

Several variants of stainless steel are viable candidates for natural gas and hydrogen pipes, each distinguished by its distinct mechanical properties and inherent characteristics. The predominant stainless steel alloys used in natural gas and hydrogen blending pipes applications include 304L and 316L.

The 304L stainless steel variant represents a low-carbon iteration of 304 stainless steel, notable for its greater weldability and lower susceptibility to corrosion. Its commendable mechanical attributes further emphasize its suitability for use in hydrogen piping contexts.

At the same time, 316L stainless steel resembles its 304L counterpart. However, a key differentiation lies in its increased molybdenum content. This increase translates into greater corrosion resistance, making 316L particularly suited to thriving in environments characterized by high corrosion potential. In particular, its robust resistance to pitting and crevice corrosion reinforces its position. In addition, 316L demonstrates resilience in the face of high pressures and has favorable mechanical properties, further consolidating its suitability for integration into hydrogen and natural gas piping systems.

Table 2 shows the constituents of both stainless steels, 3104L and 316L.

Table 2- Constituents of the 304L and 316L alloy(55, 56)

Stainless Steel	304L	316L
Carbon [%]	0.03 Max	0.03 Max
Manganese [%]	2 Max	2 Max
Phosphorus [%]	0.045 Max	0.045 Max
Sulfur [%]	0.03 Max	0.03 Max
Silicon [%]	0.75 Max	0.75 Max
Chromium [%]	16-18	16-18
Nickel [%]	8-12	10-14
Nitrogen [%]	0.1 Max	0.1 Max
Molybdenun [%]	-	2-3

The selection of an appropriate stainless steel alloy for GRMS, requires a comprehensive evaluation of various mechanical properties. In this context, a comparative analysis between two prevalent options, namely 304L and 316L stainless steels, serves as a pivotal consideration. By scrutinizing their respective compositions and characteristics, a more informed decision can be reached concerning their suitability for the specific demands of the application.

In Table 3, tensile strength and yield stress are fundamental indicators of a material's ability to withstand external forces. In this aspect, stainless steel 304L exhibits a commendably higher tensile strength of 517 MPa, surpassing the 482 MPa recorded for 316L. Moreover, the 304L alloy presents an elevated yield stress of 207 MPa, in contrast to 316L's 172 MPa. These values suggest that 304L may offer superior mechanical resilience under applied loads.

Elongation measures a material's ductility under stress, with both alloys demonstrating an equal elongation percentage of 40%. However, when evaluating hardness, 316L stainless steel has a maximum hardness of 217 HB, surpassing the 201 HB hardness of 304L. This indicates that 316L potentially offers superior resistance to indentation and scratching, which for this application is not very advantageous. Nevertheless, an increase in hardness means an increase in the probability that brittle failure will occur over time, which is why the 304L alloy is more advantageous at this point because it has less hardness.

Table 3- Mechanical properties of the 304L and 316L alloys(55, 56, 57)

Stainless Steel	304L	316L
Min tensile strength [MPa]	517	482
Min yield stress 0.2% [MPa]	207	172
Density [kg/m ³]	7890	8030
Thermal conductivity [W/m.K]	16.3	16.2
Elongation [%]	40	40
Maximum hardness [HB]	201	217
Modulus of elasticity [GPa]	193	200
Melting range [°C]	1371-1421	1371-1400

In the pursuit of identifying the most suitable material for the crucial task of gas measurement and regulation within stations, a meticulous evaluation of various stainless steel options was undertaken. Among the contenders, stainless steel 304L emerged as the prudent and optimal choice for this specialized application. It has a higher minimum tensile strength and yield stress which is good because in this situation the security coefficient relatively to the pressure increases. Finally, 304L is less expensive and has a lower hydrogen permeability than 316L.

4 Engineering Design

In this chapter, the technical details that were considered when remodeling the GRMS in Valongo will be discussed in detail. To do this, it was necessary to define temperatures, pressures, flow rates and the sizing of the pipework throughout the station. Finally, all the elements chosen for the correct operation of the entire GRMS will be shown.

In order to begin this project, given that it is a GRMS belonging to the company REN - Redes Energéticas Nacionais, some specifications imposed by the company had to be met. This information is shown in Table 4.

Table 4- Valongo GRMS specifications

Total volumetric flow rate [Nm ³ /h]	Inlet pressure [Bar]	Outlet pressure [Bar]	Inlet temperature [°C]	Outlet temperature [°C]	Volumetric fraction of H ₂ [%]
32000	72	16	10	6	20

4.1 Sizing of ducts

The first stage in the design of the GRMS is the design of the ducts, as this is where the rest of the project will be based. To do this, we'll have to use the basic information provided by REN, which is detailed in Table 5.

Table 5- Data provided by REN

Volumetric flow rate [Nm ³ /h]	Volumetric fraction of H ₂ [%]	Inlet temperature [°C]	Outlet temperature [°C]
32000	20	10	6

The first step is to calculate the volume flow of both hydrogen and natural gas, using the equation 5 e 6 respectively:

$$\dot{V}_{H_2} = \dot{V}_{Total} \times \%H_2 \quad (5)$$

$$\dot{V}_{NG} = \dot{V}_{Total} \times (1 - \%H_2) \quad (6)$$

Where:

- $\dot{V}_{Total}$, is the total volumetric flow
- $\dot{V}_{H_2}$, is the volumetric flow rate of hydrogen
- $\dot{V}_{NG}$, is the volumetric flow rate of natural gas
- $\%H_2$, is the volumetric fraction of hydrogen

From equations 5 and 6, we obtain a volumetric flow of hydrogen of 6400 Nm³/h and natural gas of 25600 Nm³/h.

There will be three different diameter dimensions within the station, one for the inlet module, filter module, pre-heating module and pressure regulation module (dimensioning 1), another for the metering module (dimensioning 2) because, as explained in the previous chapter, the flow in the metering module is divided by two lines, and finally a dimension for the outlet module (dimensioning 3). To calculate these dimensionings, it is necessary to know the following properties: total volumetric flow ($\dot{V}_{total}$), fluid temperature (T_f), maximum fluid velocity (U_{max}) and pressure (P_f), which will be applied to the equation 7 to obtain the pipeline diameter in each section. The maximum speed of the fluid will be 20 m/s, because above this speed the noise value exceeds the requirements stipulated by REN.

$$DN_{req} = \sqrt{\frac{380 \times \dot{V}_{total} \times (T_f + 273.15)}{U_{max} \times P_f \times 288.5}} \quad (7)$$

To better understand the values of the three designs, the values for each variable and the respective duct diameter are shown in Table 6.

Table 6- Values of duct diameter for each dimensioning

	Dimensioning 1	Dimensioning 2	Dimensioning 3
$\dot{V}_{total}$ [Nm ³ /h]	32000	16000	32000
T_f [°C]	10	6	6
U_{max} [m/s]	20	20	20
P_f [bar]	72	16	16
Diameter [mm]	91	136	172
DN_{req}	100	150	200
Inches	4"	6"	8"

The pipes have been oversized to ensure that there is a safety coefficient in the event of a system failure such as an increase in flow rate.

4.2 Sizing of the heat exchanger

In order to achieve a desired GRMS outlet temperature of 6°C, it becomes imperative to conduct calculations that ascertain the necessary heat input within the pre-heating module. Notably, it is established that the mixture, comprising natural gas and hydrogen, enters this module at an initial temperature of 10°C. This process occurs concurrently with a reduction in pressure from 72 bar to 16 bar within the pressure regulation module. It's important to acknowledge that this pressure drop will result in a temperature decrease due to the Joule-Thomson effect.

The initial task involves determining the Joule-Thomson coefficient. Illustrated in Figure 16 is the coefficient's correlation with the hydrogen volume fraction within the mixture and its corresponding pressure, all under a mixture temperature of 20°C. Given that the scenario here involves a hydrogen volume fraction of 20% alongside a pressure level of 72 bar (7.2MPa), the resulting Joule-Thomson coefficient stands at 0.26 K/bar.

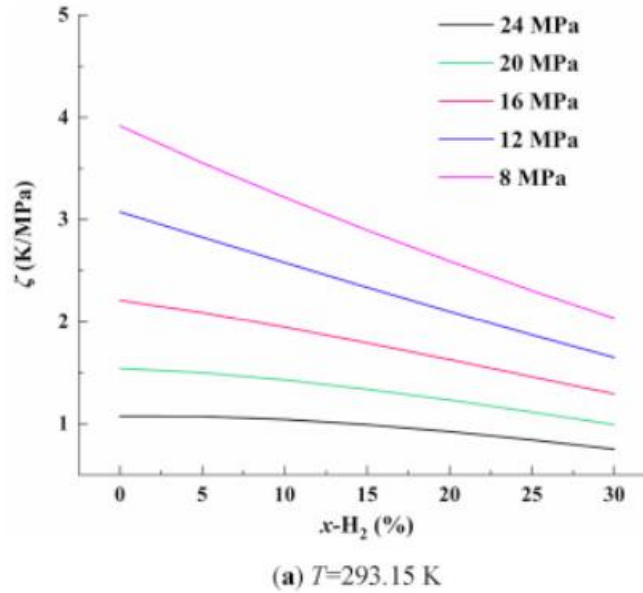


Figure 16- Joule-Thomson coefficient of hydrogen-blended natural gas with different x-H₂(58)

With the anticipation of a pressure drop amounting to 56 bar and armed with the insight into the Joule-Thomson coefficient, a deduction can be drawn indicating a temperature reduction of 14.56°C ($\Delta T_{cooling}$). Having said this, using equation 8 it is possible to determine the heating required of the fluid in the pre-heating module so that it comes out at a temperature of 6°C.

$$\Delta T = T_{final} - T_{initial} + \Delta T_{cooling} \quad (8)$$

Where:

- ΔT , is the temperature variation increasing
- T_{final} , is the final temperature
- $T_{initial}$, is the initial temperature

Table 7 shows each of the temperature values, as well as the degrees Celsius to be added to the mixture to obtain the desired final temperature after reducing the pressure.

Table 7- Value of the different temperature

T_f [°C]	T_i [°C]	$\Delta T_{cooling}$ [°C]	ΔT [°C]
6	10	14.56	10.56

4.3 Selection of the GRMS components

The successful transition towards a sustainable energy landscape demands innovative strategies in energy distribution, particularly concerning the integration of hydrogen into the existing natural gas infrastructure. The conversion of GRMS to accommodate mixed gas compositions presents a pivotal step in this evolution. As such, the selection of components within the GRMS framework becomes a critical consideration to ensure optimal performance, safety, and long-term viability.

Central to this transformation is the meticulous evaluation and choice of valves and associated components that comprise the GRMS. A paramount concern in this selection process is the potential reactivity of these materials with hydrogen gas, which could lead to the well-documented phenomenon of hydrogen embrittlement. To this end, it was ensured that the component materials were mostly made of stainless steel and that they were correctly adjusted to the required flow rates and temperatures.

4.3.1 Temperature measurement instruments

As mentioned in the previous chapter, for temperature measurement it was chosen to use a TI, a TE, both connected through a thermowell, and a TIT.

The components under consideration have been carefully chosen from the Wika product catalogue, known for its diverse selection. Among the products on offer, Wika has three different types of thermometers (TE): gas, bimetallic and liquid expansion. Given the specific context of this application, which involves scenarios close to room temperature, significant fluctuations in fluid temperature are not expected to occur quickly.

As a result, the utilization of a gas-actuated thermometer is deemed unnecessary in this context. While this variant boasts enhanced precision and quicker responsiveness to temperature fluctuations, the associated elevated costs do not warrant its adoption. In the deliberation between bimetal and liquid expansion thermometers, the preference leaned towards the bimetal option.

The R 5502 model, shown in Figure 17, was chosen for TI, with the technical data shown in Table 8.



Figure 17- Temperature indicator (59)

Table 8- R5502 TI model technical data (59)

Measuring type	Bimetal
Case material	Stainless steel
Stem material	Stainless steel
Nominal size [mm]	160
Scale range [°C]	-50...+50
Stem diameter [mm]	8
Insertion lenght [mm]	140
Unit of scale	°C
Conection process	½ Male NPT
Connector location	Radial bottom
Price [€]	203

The RTD model TR10-C, Figure 18, was chosen for the TE, but with two different configurations because one will be used for a DN100 pipe and the other for DN150 and DN200. The technical data are shown in Table 9.



Figure 18- Temperature element (60)

Table 9- RTD model TRC10-C technical data (60)

DN	100	150 and 200
Configuration sensor	Pt100	Pt100
Material	Stainless Steel/Aluminum	Stainless Steel/Aluminum
Unit of scale	°C	°C
Temperature range [°C]	-30...+300	-30...+300
Stem diameter [mm]	6	6
Insertion length [mm]	160	250
Input configuration	4 wire	4 wire
Connection process	½ Male NPT	½ Male NPT
Price [€]	376	381

The thermowell (TW) selected was the TW45-F model, Figure 19, with two different configurations because, once again, will be used for a DN100 pipe and the other for DN150 and DN200. The technical data are shown in Table 10.



Figure 19- Thermowell (61)

Table 10- TW45-F model technical data(61)

DN	100	150 and 200
Head design	Hexagon	Hexagon
Thermowell style	Form 5	Form 5
Material	Stainless steel	Stainless steel
Connection process	½ Male NPT	½ Male NPT
Connection to thermometer	½ Female NPT	½ Female NPT
Bore size [mm]	6.6	6.6
Insertion length [mm]	82	142
Price [€]	57	63

The last temperature measuring element is the temperature indicator transmitter (TIT). The T32 model shown in Figure 20 was chosen. The technical data are shown in Table 11.



Figure 20- Temperature indicator transmitter(62)

Table 11- T32 model technical data(62)

Resistance sensor	Pt100
Analog output signal [mA]	4...20
Permissible ambiente temperature [°C]	-40...+85
Response time [s]	<0.8
Price [€]	444

4.3.2 Pressure measurement intruments

Regarding pressure measurement, a pressure indicator (PI), a pressure indicator transmitter (PIT), a pressure differential indicator transmitter (PDIT) and a pressure differential indicator (PDI) were chosen. Once again, the components were meticulously chosen using the Wika and Yokogawa catalogs as reference.

The chosen PI for this application is the model 233.5, a robust stainless-steel bourdon tube pressure gauge, as illustrated in Figure 21. The decision to opt for a bourdon tube measurement, as opposed to a diaphragm solution, was grounded in its remarkable precision and resilience, aligning perfectly with the pressure ranges within which this system will operate. The bourdon tube pressure gauge offers an outstanding balance of accuracy and durability, making it an ideal fit.

Another important aspect when making a decision is the price, as diaphragm tubes can be around twice as expensive as bourdon tubes. This substantial cost difference played a pivotal role in the decision-making process, without compromising on the essential performance and reliability criteria.



Figure 21- Pressure indicator(63)

Since there will be two sections of the station with very different pressure values, pressure gauges with different pressure ranges will be needed. So there will be one pressure gauge for the 72 bar section and another for the 16 bar section. The technical data are shown in Table 12.

Table 12- PI model technical data

	For 72 bar section	For 16 bar section
Measuring type	Bourdon tube	Bourdon tube
Measuring system material	Stainless steel	Stainless steel
Case material	Stainless steel	Stainless steel
Case filling	Glycerine	Glycerine
Unit of scale	bar	bar
Nominal size [mm]	160	160
Scale range [bar]	0...160	0...40
Permissible ambient temperature [°C]	-20...+60	-40...+60
Process connection	½ NPT	½ NPT
Connection location	Lower mount	Lower mount
Price [€]	369	258€

Concerning the Pressure and Temperature Indicator (PIT), the model PGT23.100 was selected, visually depicted in Figure 22. Technical data specifications for this model can be found in Table 13.



Figure 22- Pressure indicator transmitter(64)

Table 13- PIT model technical data(64)

Case material	Stainless steel and plastic, IP 66/67
Unit of scale	Bar
Scale range [bar]	0...100
Output signal [mA]	4...20, 2-wire
Accuracy [%]	0.1
Process connection	½ NPT
Price [€]	1072

The model 732.51 from Wika catalogue, Figure 23, was chosen for the PDI. The technical data are shown in Table 14.



Figure 23- Pressure differential indicator(65)

Table 14- 732.51 model technical data(65)

Case material	Stainless steel
Case filling	Yes
Unit of scale	bar
Nominal size [mm]	160
Scale range [bar]	0...2.5
Permissible ambient temperature [°C]	-20...+60
Process connection	2 x ½ NPT male
Connection location	Lower mount
Price [€]	1548

The final essential component for pressure measurement within this system is the pressure differential indicator transmitter (PDIT). The designated model EJA110E is visually represented in Figure 24. This PDIT is from Yokogawa catalogue and the technical specifications for this instrument are provided in Table 15 for reference.



Figure 24- Pressure differential indicator transmitter(66)

Table 15- EJA110E model technical data(66)

Case material	Stainless steel
Unit of scale	Bar
Scale range [bar]	0...5
Output signal [mA]	4...20
Accuracy [%]	0.1
Response time [ms]	90
Process connection	2 x ½ NPT female
Price [€]	-

4.3.3 Filter

The inclusion of a filter within this system holds significant importance due to its role in effectively removing potentially harmful particles. These particles have the potential to cause damage to various valves within the system. To mitigate this risk, a suitable filter was meticulously chosen from Pietro Fiorentini catalogue, identified as the HFA/2 model, illustrated in Figure 25.



Figure 25- Filter(67)

Table 16 contains several of the key technical specifications for this component.

Table 16- HFA/2 model technical data

Design pressure [bar]	Up to 100
Temperature range [°C]	-10...100
Filtering capacity [	5
Filtering efficiency [%]	98
Material	Stainless steel
Price [€]	-

4.3.4 Safety elements

Safety valves have the function of ensuring the safety of systems, preventing potential overpressure situations that could lead to catastrophic consequences. The process of choosing the appropriate safety valves is a multifaceted endeavor that requires a deep understanding of system dynamics, operational requirements, and safety regulations.

Commencing with the ball valves, the implementation of the GRMS encompasses the integration of three distinct models, each varying in diameter. The initial ball valve selected originates from the Pekos catalog and is identified as model GKS 66 SGSGV CL600 4"-24", as illustrated in Figure 26. Notably, this model is accessible in DN100, DN150, and DN200 variants. For comprehensive insight, the technical particulars of each individual variant are presented in Table 17.

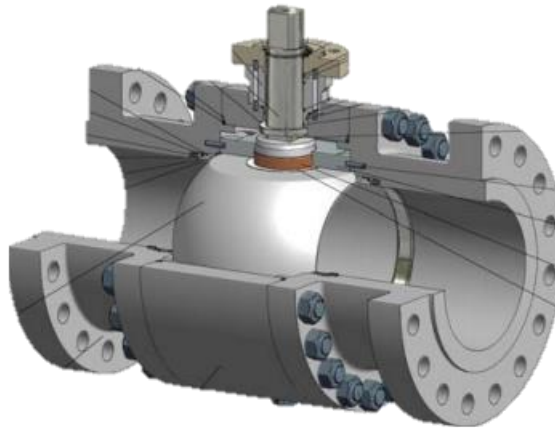


Figure 26- DN100/150/200 ball valve(68)

Table 17- GKS 66 SGSGV CL600 4"-24" model technical data(68)

DN	100	150	200
Material	Stainless steel	Stainless steel	Stainless steel
Torque [Nm]	715	1580	2500
Connection process	Flanged	Flanged	Flanged
Weight [kg]	10.8	23.2	41.5
Price [€]	-	-	-

The next chosen ball valve model, likewise sourced from the Pekos catalogue, is identified as model Z 66 RRRGV CL600 1/2"-2", as depicted in Figure 27. This specific valve has been selected in DN25 size. Comprehensive technical specifications for this model are outlined in Table 18 for reference.

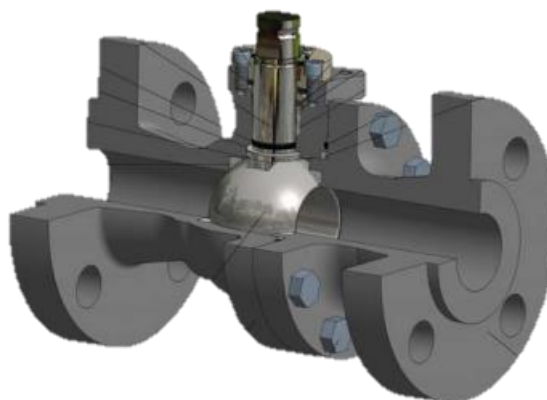


Figure 27- DN25 ball valve(69)

Table 18-Z 66 RRRGV CL600 1/2"-2" model technical data(69)

DN	25
Material	Stainless steel
Torque [Nm]	48
Connection process	Flanged
Weight [kg]	0.9
Price [€]	-

Lastly, the SS-45S12MM model, as illustrated in Figure 28, was the designated choice from the Swagelok catalogue. This selection aligns with our project's requirements. The detailed technical information for this model is presented in Table 19, offering a comprehensive overview of its specifications.



Figure 28- DN15 ball valve(70)

Table 19- 45S12MM model technical data(70)

DN	15
Material	Stainless steel
Maximum working pressure [bar]	172
Connection process	Compression type 12mm
Operation temperature range [°C]	-10...+65
Price [€]	381

Furthermore, an actuator was meticulously chosen to complement the aforementioned ball valves in DN100 and DN200 sizes. This actuator selection was made from the Auma catalogue, specifically opting for the SQEx 12.2 and 14.2 models, as showcased in Figure 29. A comprehensive breakdown of the technical specifications can be found in Table 20. This cohesive choice of actuators, perfectly compatible with the chosen ball valves, reinforces the system's operational efficiency.



Figure 29- DN100/200 actuator for ball valve(71)

Table 20- SQEx 12.2 and 14.2 models technical data(71)

Model	SQEx 12.2	SQEx 14.2
ISO 5211	F12	F16
Torque range [Nm]	50...2400	50...2400
Operating time ranges for 90° [s]	4 to 100	4 to 100
Price [€]	-	-

Subsequently, the gate valves were meticulously curated from the ARI Armaturen catalogue, with the ARI Stobu 006 model, depicted in Figure 30, emerging as the preferred option. This particular model found its application across a range of sizes: DN15 and DN25. For a comprehensive grasp, the detailed specifications of these valves are meticulously presented in Table 21. The discerning selection of the ARI Stobu 006 model exemplifies a harmonious alignment with the project's requisites.



Figure 30- DN15/25/50 gate valve(72)

Table 21- ARI Stobu 006 PN16-40 model technical data(72)

DN	15	25
Material	Stainless steel	Stainless steel
Weight [kg]	4.8	7.1
Process connection	Flanged	Flanged
Price [€]	-	-

In conjunction with the gate valves and ball valves, the inclusion of Pressure Safety Relief Valves (PSV) was paramount. To fulfill this need, a DN15 PSV was deliberately selected from the Swagelok catalogue, specifically the SS-R4S8 model, showcased in Figure 31. Additionally, a DN25 PSV was chosen from the ARI Armaturen catalogue, identified as the ARI-SAFE-TCP 961 model, depicted in Figure 32. Elaborate technical particulars for both these PSV models are meticulously documented in Table 22 and Table 23.



Figure 31- DN15 PSV(73)

Table 22- SS-R4S8 model technical data

Material	Stainless steel
Connection process	½ Male NPT
Maximum working pressure [bar]	413
Operation temperature range [°C]	-40...+150
Price [€]	390.8



Figure 32- DN25 PSV(74)

Table 23- ARI-SAFE-TCP 961 model technical data(74)

Material	Stainless steel
Temperature range [°C]	-10...+300
Nominal pressure	PN100
Connection process	Flange DIN EN 1092-1
Price [€]	-

The Slam Shut Valve was a pivotal consideration, sourced from the Honeywell catalogue, where the model HON 711 emerged as the optimal choice. Figure 33 visually represents this selected model, while Table 24 provides a comprehensive overview of its technical specifications.



Figure 33- Slam shut valve(75)

Table 24- HON 711 model technical data(75)

DN	80
Maximum operating pressure [bar]	100
Outlet pressure range [bar]	0.05 to 90
Response time [s]	0.1 to 0.3
Connection process	Flanged
Price [€]	14126

Concluding the spectrum of safety components, the Insulating Coupling was meticulously selected from the Zunt catalogue, as depicted in Figure 34. The accompanying technical specifications can be perused in detail within Table 25.



Figure 34- Insulating coupling(76)

Table 25- Zunt standard model technical data(76)

DN	100 and 200
Temperature range [°C]	-10...70
Electrical resistance	In dry conditions 25MOhm – 1000 V DC
Coating	Epoxy resin
Price	-

4.3.5 Pressure control valve

In the process of determining the optimal pressure control valve, the Honeywell catalogue guided our selection, ultimately leading to the choice of the HON 512 model, depicted in Figure 35. For comprehensive insight into its specifications, Table 26 provides a detailed breakdown of the technical data.



Figure 35- Pressure control valve(77)

Table 26- HON 512 model technical data(77)

DN	50 to 150
Maximum operating pressure [bar]	100
Outlet pressure range [bar]	0.3 to 90
Minimum pressure drop [bar]	1.5
Connection process	Flanged
Price [€]	25676

4.3.6 Flow measurement valve

In the process of selecting the appropriate turbine meter, thorough consultation of the RMG catalogue led us to opt for the model TRZ 03-G1000, as illustrated in Figure 36. For a comprehensive understanding of its specifications, refer to Table 27, which provides a detailed breakdown of the technical data.



Figure 36- Turbine meter(78)

Table 27- TRZ 03 – G1000 model technical data(78)

DN	150
Maximum operating pressure [bar]	100
Maximum flow rate [m ³ /h]	1600
Accuracy [%]	± 0.5
Price [€]	-

4.3.7 Heat exchanger

The heat exchanger is a crucial element within the scope of this thesis, playing a pivotal role in the system. After careful consideration, the heat exchanger model KSI from Pietro Fiorentini was selected as the optimal choice. It's important to note that each heat exchanger is meticulously sized and tailored to the unique specifications of each project. This intricate sizing process is expertly conducted by Pietro Fiorentini, ensuring that the heat exchanger seamlessly integrates into the overall system and effectively fulfills its designated functions. Figure 37 shows the KSI model and the technical data are shown in Table 28.



Figure 37- Heat exchanger(79)

Table 28- KSI model technical data(79)

Heating fluid	Water
Maximum working pressure	According to design conditions
Maximum working temperature [°C]	100
Price [-]	-

4.3.8 Five way valve

In the process of selecting the five-way valve, we referred to Swagelok's catalogue and ultimately opted for the model SS-V5NBF8, depicted in Figure 38. Comprehensive technical specifications for this model are outlined in Table 29.



Figure 38- Five way valve(80)

Table 29- SS-V5NBF8 model technical data

Material	Stainless steel
Temperature range [°C]	-65...450
Connection 1	½ Female NPT
Connection 2	½ Female NPT
Connection 3	½ Female NPT (vent)
Price [€]	665.26

4.4 Final model of the GRMS

In the final stage of this study, it becomes feasible to establish a comprehensive array of prerequisites that will govern the operation of the control system. These requirements serve as crucial benchmarks to ensure the efficient and safe functioning of the remodeled GRMS in the context of its newly integrated hydrogen and natural gas mixture. The specifics of these criteria are detailed in Table 30, where the prescribed parameters for pressure, volumetric flow rate, temperature, and pipe diameter at the inlet of the GRMS are clearly outlined.

Table 30- Final conditions at the inlet of the GRMS

Temperature [°C]	10
Volumetric flow rate [Nm³/h]	32000
Pressure [bar]	72
Pipe diameter	DN100

The Table 31 also presents analogous values for these parameters as they pertain to the outlet of the GRMS.

Table 31- Final conditions at the outlet of the GRMS

Temperature [°C]	6
Volumetric flow rate [Nm³/h]	32000
Pressure [bar]	16
Pipe diameter	DN200

It's important to underscore that these stipulated values are instrumental in maintaining the integrity and stability of the gas mixture within the station. The pressure values ensure that the mixture remains within safe operating limits, guaranteeing the protection of both personnel and equipment. Concurrently, the volumetric flow rate parameters govern the rate of gas transfer, which is pivotal for optimal station performance. Temperature specifications, on the other hand, safeguard against any adverse thermal effects that could potentially compromise the mixture's composition or the station's infrastructure. Lastly, the prescribed pipe diameter values are indicative of the appropriate conduit size to accommodate the desired flow.

Having established the prerequisites necessary for the seamless operation of the entire system, the pending task involves executing the projected budget required for the implementation of the hydrogen injection and blending system within the natural gas network. The outcomes of this financial analysis are meticulously detailed in Table 32.

Table 32- Predictable budget for all components

Element	Quantity	Price per unit [€]	Total Price [€]
Ball valve DN200	2	-	-
Ball valve DN150	11	-	-
Ball valve DN100	14	-	-
Ball valve DN25	15	462	6930
Ball valve DN15	34	381	12954
Actuator for ball valve DN200	1	-	-
Actuator for ball valve DN100	1	-	-
Gate valve DN25	10	-	-
Gate valve DN15	22	-	-
PCV	2	25676	51352
PSV DN25	2	-	-
PSV DN15	4	390.8	1563
SSV	4	14126	56504
Filter	2	-	-
Turbine meter	3	19000	57000
Heat exchanger	2	-	-
Insulating coupling	2	-	-
Five way valve	2	665.26	1330
PDI	2	1548	3096
PIT	2	1072	2144
PI for 72 bar section	6	369	2214
PI for 16 bar section	3	258	774
PDIT	2	-	-
TW DN150/200	7	63	441
TW DN100	3	57	171
TE DN150/200	4	381	1524
TE DN100	1	376	376
TI	5	203	1015
TIT	1	444	444
		Total	199833

Certain components lack pricing information due to various reasons. In some instances, the company did not respond promptly to inquiries regarding this dissertation's delivery. In other cases, companies did not disclose component pricing as they only provide such details to their registered clients.

5 Conclusions

The main aim of this dissertation was to redesign the Valongo GRMS so that it can run on a blend of natural gas and hydrogen.

To commence this endeavor, an extensive examination was undertaken to delve into diverse aspects concerning hydrogen. This comprehensive study encompassed an exploration of hydrogen's characteristics, its production techniques, and its behavior when combined with natural gas. Furthermore, a meticulous investigation was conducted to assess its interaction with the various materials comprising the station. Ultimately, the research also delved into comparable refurbishment projects undertaken at other stations. This investigation played a crucial role in elucidating that while hydrogen possesses favorable attributes for fossil fuel substitution, its handling necessitates the utmost caution and strict safety measures due to its potential hazards.

Following an in-depth analysis of the current state of technology and a comprehensive grasp of the risks and obstacles associated with hydrogen in the system's evolution, a (P&ID) was meticulously devised. This stage of system development proved to be highly demanding, as it necessitated the seamless functionality of all components, ensuring not only their safety but also their precise control mechanisms to prevent any mishaps or incidents. Regarding the control system, as anticipated, it is governed by a Programmable Logic Controller (PLC) tasked with assessing critical parameters such as pressure, temperature, and volume flow. In instances where abnormal values are detected within these parameters, the PLC promptly triggers alerts. For instance, if a filter becomes obstructed due to impurities, leading to a pressure drop that the PLC detects, it signals the need for filter replacement. Conversely, in cases of excessive pressure, the safety valves are activated.

Additionally, during this phase of the project, thorough research was conducted to identify the most suitable material for the pipelines. This is a vital consideration for ensuring both safety and the long-term durability of the installation, especially in light of hydrogen embrittlement concerns. The selected material is 304L, chosen for its low carbon content, which renders it highly resistant to hydrogen embrittlement. When combined with the material's other physical properties falling within the required values for the system, 304L emerged as the optimal choice.

In terms of system design, a meticulous set of calculations was undertaken to ascertain the required pipe diameters in adherence to safety regulations. Additionally, the determination of the necessary heat input to prevent pressure reduction from 72 bar to 16 bar, attributable to the Joule-Thomson effect, was a pivotal aspect of this evaluation. Consequently, the system was logically segmented into three distinct dimensions. Dimensioning 1, which includes the inlet module, filter module, preheating module and pressure regulation module; dimensioning 2, which includes the metering module; and dimensioning 3, which includes the output module. This division allowed for tailored solutions to accommodate the specific pressure and temperature requirements of each module, thus dictating the differentiated pipe diameters for optimal system performance.

Ultimately, the selection of components essential for constructing this system was executed by thoroughly scrutinizing a variety of suppliers' catalogs.

In conclusion, hydrogen stands poised to assume a pivotal role in ushering in a cleaner and more sustainable energy era. In stark contrast to fossil fuels, hydrogen combustion yields zero emissions, and its versatility as an energy carrier allows for storage and transportation, catering to a myriad of applications. Through sustained investments in research and the advancement of hydrogen technologies and infrastructure, there exists the prospect of hydrogen entirely supplanting fossil fuels as the primary energy source. Although this transition may unfold

gradually, early investments in hydrogen have the potential to pave the way for a more environmentally friendly planet for generations to come.

6 Future work

The development of the reformulation of this station to operate with a blend of natural gas and hydrogen, within the scope of this dissertation, was carried out essentially from a theoretical point of view. The project's formulation was the result of thorough research, which included the specification of pipe materials, components, and system requirements, alongside the design of the control system.

To implement this project in practice, it would require further development of the control system, including the creation of a control program using ladder logic. Additionally, the potential incorporation of additional motorized valves within the station could enable automatic diversion of gas flow in the event of a filter blockage or issues within module lines. However, it's worth noting that this concept was not realized due to the considerable associated expenses.

It would be of considerable interest to investigate the feasibility of integrating solar panels to both provide power to the station and heat the water entering the heat exchanger. Such an initiative could potentially replace the current boilers, further enhancing the station's sustainability and eco-friendliness.

Finally, it is critical to assemble this system and subject it to real-world simulations to validate that the expected theoretical behavior and safety measures match the actual operational results.

Reference list

1. ESTRATÉGIA NACIONAL PARA O HIDROGÉNIO (EN-H2) [Available from: <https://www.portugalenergia.pt/setor-energetico/bloco-4/>].
2. Natural Gas basics: U.S. Energy Information Administration; [Available from: <https://www.eia.gov/kids/energy-sources/natural-gas/#top-container>].
3. Vandr  C, Cramer B, Gerling P, Winsemann J. Natural gas formation in the western Nile delta (Eastern Mediterranean): Thermogenic versus microbial. *Organic Geochemistry*. 2007;38(4):523-39.
4. Rice DD, Claypool GE. Generation, Accumulation, and Resource Potential of Biogenic Gas1. *AAPG Bulletin*. 1981;65(1):5-25.
5. Dawood F, Anda M, Shafiullah GM. Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy*. 2020;45(7):3847-69.
6. dos Santos KG, Eckert CT, De Rossi E, Bariccatti RA, Frigo EP, Lindino CA, et al. Hydrogen production in the electrolysis of water in Brazil, a review. *Renewable and Sustainable Energy Reviews*. 2017;68:563-71.
7. Koumi Ngoh S, Njomo D. An overview of hydrogen gas production from solar energy. *Renewable and Sustainable Energy Reviews*. 2012;16(9):6782-92.
8. Karaca AE, Qureshy AMMI, Dincer I. An overview and critical assessment of thermochemical hydrogen production methods. *Journal of Cleaner Production*. 2023;385:135706.
9. Hydrogen Colours Codes H2 Bulletin [Available from: <https://www.h2bulletin.com/knowledge/hydrogen-colours-codes/>].
10. Matthey J. Routes to hydrogen production [Available from: <https://matthey.com/products-and-markets/energy/hydrogen/types-of-hydrogen-production>].
11. Ji M, Wang J. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. *International Journal of Hydrogen Energy*. 2021;46(78):38612-35.
12. Wang J, Yin Y. Fermentative hydrogen production using pretreated microalgal biomass as feedstock. *Microbial Cell Factories*. 2018;17(1):22.
13. El-Emam RS,  zcan H. Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. *Journal of Cleaner Production*. 2019;220:593-609.
14. Abdin Z, Zafaranloo A, Rafiee A, M rida W, Lipi ski W, Khalilpour KR. Hydrogen as an energy vector. *Renewable and Sustainable Energy Reviews*. 2020;120:109620.
15. Hosseini SE, Wahid MA. Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. *Renewable and Sustainable Energy Reviews*. 2016;57:850-66.
16. Zhang B, Zhang S-X, Yao R, Wu Y-H, Qiu J-S. Progress and prospects of hydrogen production: Opportunities and challenges. *Journal of Electronic Science and Technology*. 2021;19(2):100080.
17. Brauns J, Turek T. Alkaline Water Electrolysis Powered by Renewable Energy: A Review. *Processes*. 2020;8(2):248.
18. Electrolysis iStock 2016 [Available from: <https://www.istockphoto.com/pt/vetorial/electr%C3%B3lise-experimental-configurar-por-electr%C3%B3lise-e-processo-qu%C3%ADmico-gm517845768-89688319>].

19. Burton NA, Padilla RV, Rose A, Habibullah H. Increasing the efficiency of hydrogen production from solar powered water electrolysis. *Renewable and Sustainable Energy Reviews*. 2021;135:110255.
20. Chi J, Yu H. Water electrolysis based on renewable energy for hydrogen production. *Chinese Journal of Catalysis*. 2018;39(3):390-4.
21. INEGI P. Hydrogen production.
22. Mazloomi K, Gomes C. Hydrogen as an energy carrier: Prospects and challenges. *Renewable and Sustainable Energy Reviews*. 2012;16(5):3024-33.
23. Ahluwalia RK, Peng JK. Automotive hydrogen storage system using cryo-adsorption on activated carbon. *International Journal of Hydrogen Energy*. 2009;34(13):5476-87.
24. CES Edupack. Granta Design.
25. Huang Z, Liu B, Zeng K, Huang Y, Jiang D, Wang X, et al. Experimental Study on Engine Performance and Emissions for an Engine Fueled with Natural Gas–Hydrogen Mixtures. *Energy & Fuels*. 2006;20(5):2131-6.
26. Ishaq H, Dincer I, Crawford C. A review on hydrogen production and utilization: Challenges and opportunities. *International Journal of Hydrogen Energy*. 2022;47(62):26238-64.
27. de Santoli L, Paiolo R, Lo Basso G. An overview on safety issues related to hydrogen and methane blend applications in domestic and industrial use. *Energy Procedia*. 2017;126:297-304.
28. Obanijesu EO, Barifcani A, Pareek VK, Tade MO. Experimental Study on Feasibility of H₂ and N₂ as Hydrate Inhibitors in Natural Gas Pipelines. *Journal of Chemical & Engineering Data*. 2014;59(11):3756-66.
29. Turoń K. Hydrogen-powered vehicles in urban transport systems – current state and development. *Transportation Research Procedia*. 2020;45:835-41.
30. Umicore. What are fuels cells, which types exist and how do they work? : Umicor; 2022 [Available from: <https://www.umicore.com/en/newsroom/what-are-fuel-cells/>].
31. He Z, Cui M, Qian Q, Zhang J, Liu H, Han B. Synthesis of liquid fuel via direct hydrogenation of CO₂. *Proceedings of the National Academy of Sciences*. 2019;116(26):12654-9.
32. Aydin K, Kenanoğlu R. Effects of hydrogenation of fossil fuels with hydrogen and hydroxy gas on performance and emissions of internal combustion engines. *International Journal of Hydrogen Energy*. 2018;43(30):14047-58.
33. Dodds PE, Staffell I, Hawkes AD, Li F, Grünewald P, McDowall W, et al. Hydrogen and fuel cell technologies for heating: A review. *International Journal of Hydrogen Energy*. 2015;40(5):2065-83.
34. Europe F. How fertilizers are made Fertilizers Europe [Available from: <https://www.fertilizerseurope.com/fertilizers-in-europe/how-fertilizers-are-made/>].
35. Mohamed B, Ali B, Ahmed B, Ahmed B, Salah L, Rachid D. Study of hydrogen production by solar energy as tool of storing and utilization renewable energy for the desert areas. *International Journal of Hydrogen Energy*. 2016;41(45):20788-806.
36. Argélia fecha hoje gasoduto do Magrebe que serve Espanha e Portugal. *Diário de Notícias*.

37. Agency IE. Portugal Natural Gas Security Policy IEA30/06/2022 [Available from: <https://www.iea.org/articles/portugal-natural-gas-security-policy>].
38. REN. REN publica mapas das redes de eletricidade e gás natural 2013 [Available from: https://www.ren.pt/pt-PT/media/comunicados/detalhe/ren_publica_mapas_das_redes_de_eletricidade_e_gas_natural].
39. Energy USDo. Hydrogen Pipelines: Office of Energy efficiency & renewable energy; [Available from: <https://www.energy.gov/eere/fuelcells/hydrogen-pipelines>].
40. Li H, Cao X, Liu Y, Shao Y, Nan Z, Teng L, et al. Safety of hydrogen storage and transportation: An overview on mechanisms, techniques, and challenges. *Energy Reports*. 2022;8:6258-69.
41. Sadik-Zada ER, Santibanez Gonzalez EDR, Gatto A, Althaus T, Quliyev F. Pathways to the hydrogen mobility futures in German public transportation: A scenario analysis. *Renewable Energy*. 2023;205:384-92.
42. T. Nejat Veziroglu SZ, Dmitry V. Schur, B. Baranowski, Anatoliy P. Shpak, Valeriy V. Skorokhod. *Hydrogen Materials Science and Chemistry of Carbon Nanomaterials* 2005.
43. Langmi HW, Engelbrecht N, Modisha PM, Bessarabov D. Chapter 13 - Hydrogen storage. In: Smolinka T, Garche J, editors. *Electrochemical Power Sources: Fundamentals, Systems, and Applications*; Elsevier; 2022. p. 455-86.
44. Hwang HT, Varma A. Hydrogen storage for fuel cell vehicles. *Current Opinion in Chemical Engineering*. 2014;5:42-8.
45. Graetz J. New approaches to hydrogen storage. Royal Society of Chemistry. 2008.
46. Schneemann A, White JL, Kang S, Jeong S, Wan LF, Cho ES, et al. Nanostructured Metal Hydrides for Hydrogen Storage. *Chemical Reviews*. 2018;118(22):10775-839.
47. Züttel A. Hydrogen storage methods. *Naturwissenschaften*. 2004;91(4):157-72.
48. Wu X, Zhang H, Yang M, Jia W, Qiu Y, Lan L. From the perspective of new technology of blending hydrogen into natural gas pipelines transmission: Mechanism, experimental study, and suggestions for further work of hydrogen embrittlement in high-strength pipeline steels. *International Journal of Hydrogen Energy*. 2022;47(12):8071-90.
49. Choudhary S, Vishwakarma M, Dwivedi SK. Evaluation and Prevention of Hydrogen Embrittlement by NDT Methods: A Review. *Materials Proceedings*. 2021;6(1):18.
50. Lowesmith BJ, Hankinson G, Johnson DM. Vapour cloud explosions in a long congested region involving methane/hydrogen mixtures. *Process Safety and Environmental Protection*. 2011;89(4):234-47.
51. Sánchez AL, Williams FA. Recent advances in understanding of flammability characteristics of hydrogen. *Progress in Energy and Combustion Science*. 2014;41:1-55.
52. Martin P. Hydrogen to Replace Natural Gas- by the Numbers. 2023.
53. Dong C, Zhou Q, Zhang X, Zhao Q, Xu T, Hui Se. Experimental study on the laminar flame speed of hydrogen/natural gas/air mixtures. *Frontiers of Chemical Engineering in China*. 2010;4(4):417-22.
54. NASA. Safety Standard for Hydrogen and Hydrogen Systems - Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage and Transportation. 1997.
55. GRADE 304 / 304L STAINLESS STEEL SPECIFICATION: Stainless UK; [Available from: <https://www.stainless-uk.co.uk/materials/304-304l/>].

56. GRADE 316/316L STAINLESS STEEL SPECIFICATION SHEET: Stainless UK; [Available from: <https://www.stainless-uk.co.uk/materials/316-316l/>].
57. The difference between 304, 304L, 316 and 316L: The main chemical and mechanical differences: Nordic Steel; [Available from: <https://en.nordicsteel.no/fagartikler/forskjellen-pa-304-304l-316-og-316l>].
58. Li Z, Zhang C, Li C, Wu X, Xie H, Jiang L. Thermodynamic evaluation of the effects of hydrogen blending on the Joule-Thomson characteristics of hydrogen-blended natural gas. Journal of Cleaner Production. 2023;406:137074.
59. Bimetal thermometer for the process industry per EN 13190, premium version Model 55: Wika; [Available from: <https://www.wika.com/en-gb/55.WIKA>].
60. Threaded resistance thermometer
With protection tube
Model TR10-C [Available from: https://www.wika.com/en-ae/tr10_c.WIKA].
61. Threaded protection tube
Design per DIN 43772 form 5, 8
Model TW45 [Available from: <https://www.wika.com/en-gb/tw45.WIKA>].
62. Digital temperature transmitter T32 [Available from: https://www.wika.com/en-ae/t32_xs.WIKA].
63. Bourdon tube pressure gauge, stainless steel [Available from: https://www.wika.com/en-gb/232_50_233_50.WIKA].
64. Process transmitter
Model UPT-20 [Available from: https://www.wika.com/en-ae/upt_20_upt_21.WIKA].
65. Differential pressure gauge [Available from: https://www.wika.com/en-sg/732_31_732_51_733_31_733_51.WIKA].
66. EJA110E Differential Pressure Transmitter [Available from: <https://www.yokogawa.com/solutions/products-and-services/measurement/field-instruments-products/pressure-transmitters/differential-pressure/eja110e/>].
67. HFA – HFB FILTERS [Available from: <https://www.fiorentini.com/en/solutions/products/gas-filters/hfa-hfb-filters/>].
68. PEKOS FIG.GKS 66 SGSGV CL600 4"-24" [Available from: <https://www.pekos.es/downloads/fig.gks-66-sgsgv-cl600-4-24-565.pdf>].
69. Pekos Z 66 RRRGV CL600 1/2"-2" [Available from: <http://www.pekos.es/downloads/fig.z-66-rrrgv-cl600.pdf>].
70. Stainless Steel 1-Piece 40 Series Ball Valve, 12 Cv, 12 mm Swagelok Tube Fitting [Available from: <https://products.swagelok.com/en/c/2-way-straight-pattern/p/SS-45S12MM?q=:relevance:bodyMaterial:316+Stainless+Steel:connection1Size:12+mm>].
71. Explosion-proof actuators SQEx and SQREx [Available from: <https://www.auma.com/en/products/part-turn-actuators/explosion-proof-actuators-sqex-and-sqrex/>].
72. ARI-STOBU 006 PN16-40 [Available from: <https://www.ari-armaturen.com//products?baureihe=006&einsatzbereich=2&produktgruppe=10&cHash=5d8c530e77f5cbb9337ffe8302d256a6>].

73. Stainless Steel High Pressure Proportional Relief Valve, 1/2 in [Available from: <https://products.swagelok.com/en/c/high-pressure-relief-valve/p/SS-R4S8>.
74. ARI-SAFE-TCP 961/962/963 [Available from: https://www.ari-armaturen.com/_appl/files_tb/files/900005-2.pdf.
75. HON 711 - DN 25 thru 150 [Available from: <https://process.honeywell.com/us/en/products/gas/regulators-and-safety-accessories/safety-shut-off-valves/hon-711-dn-25-thru-150>.
76. Zunt- standard soldado [Available from: <https://www.contagas.com/pt/productos-y-soluciones/protecao-de-rede/juntas-dielectricas/standard-soldado/>.
77. HON 512 [Available from: <https://process.honeywell.com/us/en/products/gas/regulators-and-safety-accessories/high-pressure-regulators-up-to-ansi-600/hon-512>.
78. Turbine gas meter TRZ 03 [Available from: <https://www.rmg.com/en/products/gas-meter/turbine-gas-meter/trz-03>.
79. GAS HEAT EXCHANGERS (KSI) [Available from: <https://www.fiorentini.com/en/solutions/systems/gas-treatment/gas-heat-exchangers-ksi/>.
80. Stainless Steel 5-Valve Instrument Manifold, 1/2 in. Female NPT, Ball Tip [Available from: <https://products.swagelok.com/en/c/5-valve-ball-stem/p/SS-V5NBF8>.

ANEXO A: P&ID of the GRMS

