Introduction of H2 in the Natural Gas Network

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Abstract

This document is prepared as a master's degree thesis which addresses Instituto Superior Técnico and AGH University of Science and Technology. The study presented in the thesis is developed by the author, REN - Rede Eléctrica Nacional, IST Lisboa and AGH Krakow cooperatively. The research presented aims to give an overview and suggestions to REN in their hydrogen injection project. In the following years the company wants to give a transferring service to hydrogen producers. Therefore, there is a need for investigation of the current equipment and its adaptations to hydrogen injection. The focus of this study which is defined by REN is hydrogen injection into natural gas grid in Portugal. There are several hydrogen injection projects ongoing in the literature. The thesis points out the most recent developments, obstacles, and constraints to adapt hydrogen technologies into an existing natural gas grid. In the full scope of the project, assessment of the REN's natural gas transmission system, identification of the legislation, regulation and security standards of hydrogen injection, analysis of the adaptations of steel pipeline and other assets, new approaches to gas monitoring, potential derating of the infrastructure depending on hydrogen percentage injected are studied.

Introduction

Clean energy production, energy security and climate change are the hottest topics which humanity tackles in today's world. Organizations and developed countries have changed their perception of energy production. Green energy production, decarbonization and a future with less fossil fuels is the new target. Although, there are many solutions available, the interest to hydrogen technologies keeps increasing. There are several reasons why hydrogen has a key role in the energy sector. Firstly, hydrogen has a unique carbon free nature and high calorific value when it is combusted. Every other fuel which is used today emits CO_2 or CO. It is a well-known chemical fact that when H_2 enters a reaction with O_2 the main products are heat and water. All around the world, organizations are trying to avoid emitting CO_2 due to its obvious hazards to human health and to the nature. If, hydrogen becomes the primary energy source in the world, the carbon emissions caused by energy production will be simply zero. Secondly, hydrogen may provide energy security everywhere in the world. Natural gas, oil, coal, and other fossil fuels are abundant in specific locations all around the globe. While some locations are rich and fortunate about their resources, some locations are without any energy sources. However, hydrogen can be produced from off-peak electricity and access electricity produced from renewable energy sources. This kind of hydrogen production gives a key alternative to energy storage methods which are still developing today. Thirdly, hydrogen has the potential to replace almost all the fossil fuels. It can be used in natural gas systems, powerplants and even in the mobility devices. Although, there are numerous benefits of hydrogen in energy sector, the infrastructure for hydrogen is still insufficient. That is why, one of the most logical usage of hydrogen is the injection into the natural gas networks. Within the scope of the thesis REN wants to investigate the hydrogen injection possibilities soon. According to the new strategy developed by Portuguese government 5% hydrogen injection into the natural gas system will be an obligation. The counterparts of these law will be seen in European Union in the near future as a part of decarbonization and green energy act. REN plans to transfer hydrogen provided by producers. The company will not produce hydrogen or develop a business plan focusing on hydrogen technologies. Instead, REN will be responsible for hydrogen and natural gas blending which will be relatively simple. The operation of hydrogen injection seems easier than the creating a circular hydrogen economy. However, there are still a lot of concerns about the system integration, operation costs, safety, and complexity. Under the scope of this master's thesis all the relative aspects are considered and investigated.

Every organization or company in the world would like to investigate the effects of their new business model to the existing model. In REN's case, the company already has functioning business model and a transmission system. It is known that building a gas transmission system only for hydrogen will come with great capital costs. Therefore, introducing hydrogen into an existing pipeline network with small retrofitting and adaptations is more cost effective. In one hand, injecting hydrogen will provide numerous benefits like compliance with new law and decarbonization. On the other hand, there are possible disadvantages which may affect the current equipment and operations. REN wants to inject maximum possible hydrogen by volume into their natural gas network. While injecting hydrogen there are crucial topics to be examined. In Chapter 2 of this thesis, these topics are determined as safety, leakage, durability, integrity, and impact to the end user.

European Union has announced its intention to be carbon neutral by 2050. This initiative on the path of a carbon neutral future has major impacts on the natural gas sector. Natural gas plays a significant role in the energy mixture for many countries that is why natural gas industry has well-established regulations, especially in Europe. However, these law and regulations need adaptations because of the developing nature of energy production and transportation. Hydrogen and other low carbon gases provide an opportunity to meet the decarbonization targets but even so, many of the law fails to mention hydrogen injection into natural gas systems. The purpose of Chapter 3 is making hydrogen injection into natural gas network safe, reliable, consumer-friendly, efficient, and environmentally friendly by law. Therefore, European law and legislations are examined under several categories.

Analysis of the Changes and Adaptations in the System

Hydrogen injection into natural gas network may result in several changes in the system and the operation conditions depending on the hydrogen concentration. One of the most important changes that is faced would be the properties of natural gas mixture. In the gas transmission business fluid mechanics and gas quality parameters are crucial for sustainability and profitability purposes. Under this sub-chapter the changes in the gas quality are primary calculated with assumptions. Furthermore, the possible alteration effects and adaptations are analyzed. The hydrogen ranges are determined under the light of Portuguese governments and REN's hydrogen strategy. Therefore, many of the calculations are performed up to 20%-30% of hydrogen concentration in natural gas.

On one hand a significant decrease is observed in the lower hating value and higher heating value of the natural gas mixture, especially when hydrogen concentration exceeds 30%. On the other hand, the decrease in the wobbe index is relatively smaller. Initially REN plans to blend the natural gas by 5%. According to REN's plan approximately 3.46%, 3.37% and 1.02% decrease is expected in lower heating value, higher heating value and wobbe index respectively. These changes are shown in percentage in Table 1. Initially this drawback does not require an adaptation because it can be fixed by changing some of the service conditions. However, in the future if hydrogen concentration exceeds 20% in the gas mixture there will be a need for further research and adaptations.

Table 1 Decrease in lower heating value, higher heating value and wobbe index with increasing hydrogen percent by volume

Hydrogen percent	LHV Decrease(%)	HHV Decrease(%)	Wobbe Index Decrease (%)
0	0	0	0
5	3,458684173	3,367231493	1,020415038
10	6,917368346	6,734462986	2,030913409
15	10,37605252	10,10169448	3,02778987
20	13,83473669	13,46892597	4,00639935
25	17,29342086	16,83615747	4,960870921
30	20,75210504	20,20338896	5,883713878

REN's natural gas network connects many locations, and these locations are connected with pipelines which has different diameters according to the needs. Therefore, every single connecting pipeline contains different amount of energy. This energy is represented by the term called Line Pack and it is the inventory of gas in a pipeline.[1] In this section four pipelines which has different diameters are chosen to calculate hydrogen injection effect on line-pack. The line pack change between important connections in REN's pipeline is given in Table 2. Line pack is directly proportional to the volume of the pipeline. That is why pipelines with higher diameter and longer distances suffer from the line pack lose more than others.

Pressure is one of the most important parameters in the natural gas industry because it has the potential to affect every single equipment and component. As it was mentioned previously in this Chapter 4 pressure change also has the potential to balance delivered energy amount loss due to hydrogen injection. Moreover, the planning and design of the stations and pipeline is done according to the pressure modification in the transmission network. Clearly without the increased levels of pressure, it would not be possible to transport hydrogen or natural gas for long distances. Therefore, terms like pressure drop and operating pressure plays a key role in the industry. That is why it is fundamentally important to understand how hydrogen injection would affect the pressure. For pressure drop calculations in the pipeline Panhandle B equation is used because of its suitability for high pressure and turbulent flow characteristics. The pipeline is assumed to be completely horizontal. Therefore, change in potential energy is neglected.

The calculated pressure drops with in 17km distance is shown in Figure 1 with changing hydrogen percentages. The obvious conclusion from that figure is when hydrogen concentration increases in the natural gas mixture, the pressure drop will be less. The main reason behind this conclusion is the increase in pseudo compressibility factor, decrease in the viscosity and the decrease in the relative density with increased level of hydrogen injection.

Table 2 Changes in the line-pack depending on hydrogen percentage through pipeline.

Hydrogen Percentage	Line Pack Between Given Locations in KWh			
	Setubal Leira	Braga Valença	Monforte Guarda	Sines Setubal
0% Hydrogen	2875763,604	627599,7012	561786,5433	1888905,479
5% Hydrogen	2778929,986	606466,9664	542869,8899	1825301,659
10% Hydrogen	2682096,368	585334,2316	523953,2365	1761697,839
15% Hydrogen	2585262,751	564201,4968	505036,5831	1698094,019
20% Hydrogen	2488429,133	543068,762	486119,9297	1634490,198

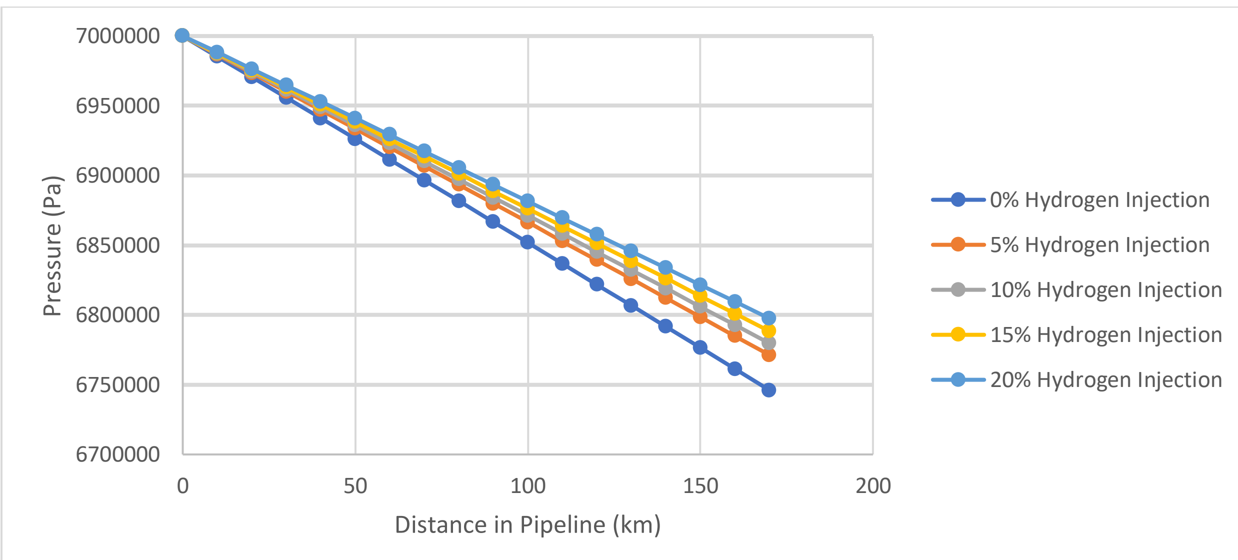

Figure 1 The effect of hydrogen injection in pressure drop.

In REN's hydrogen strategy there is a major adaptation, and it is building a blending station. This adaptation is based on the business case of the project. According to the case, hydrogen producers are responsible for connecting their hydrogen to the natural gas operator. Therefore, REN will not produce hydrogen instead they will be responsible only for the transportation of it. Due to possible mixing problems and possible agglomeration of hydrogen, blending of natural gas and hydrogen before injection is desired. The location, the size and the capacity of the blending station has not been decided. However, one thing is certain, the blending equipment must be big enough to blend REN's transmission volume. With this type of blending operation REN aims to homogenize and control hydrogen concentration through the natural gas network.

Gas Quality Monitoring

The concept of gas quality determines general properties of gas in terms of chemical composition and thermodynamics. Natural gas usually has a complex chemical composition which includes different types of hydrocarbons and trace elements. The main components of a natural gas mixture can be listed as CH_4, C_2H_6, C_3H_8, C_4H_{10}, N_2 and CO_2.The chemical composition of the natural gas is often required by chemical and process industries. However, instead of defining the gas by its composition some key parameters are used. Some of the most important parameters are used to explain the quality of the gas. These parameters are known as superior calorific value, inferior calorific value, density, wobbe index, hydrocarbon dew point, Joule-Thompson coefficient, and methane number.[2] Each parameter is used for a specific purpose, and they are explained in detail later in this chapter. The composition and quality parameters of natural gas vary depending on the origin, upgrading and transport routes. [3] The thermodynamic state plays an important role with respect to reference condition of storage and transportation. Moreover, it is shaped by temperature and pressure of the gas.

The measurement of the quality of the gas is the basis of commerce among producers, royalty owners, transporters, process plants, and federal government authorities. Because of the size of the natural gas sector, measurement of hydrocarbons has a significant impact on the Gross National Product of exporting and importing countries. [4] Any error in the measurement of the parameters may affect the profit both in short and long term. In addition to the effects on profit, the inaccurate measurements can cause legal liabilities, loss of costumers and adverse publicity. [4] In many gas markets, gas quality must be known prior to supply and transportation, and therefore it is often a prerequisite for custody transfer. [5] That is why in the European market standards are strictly audited and companies are expected to base their business on accurate measurement of the gas quality.

In general, gas quality measurement even of natural gas improves process quality with regard to safety, efficiency, and emissions. This indicates an emerging need for gas quality metering instruments with changed specifications addressing especially the renewable gases. The share of renewable gases like hydrogen and biogas in the market is increasing because of the national and international climate change policies and laws. For this reason, the quality of the natural gas is expected to chance more often than usual. [6]

In this chapter the definitions and the importance of gas quality parameters are mentioned. Different approaches of determining gas quality are presented and examined based on the physicochemical properties. Moreover, essential regulatory framework and standards of gas quality is introduced. In addition, recent developments and new approaches to gas quality monitoring is investigated.

Gas chromatography (GC) is a separation technique used to isolate volatile components of a mixture depending on differences in the mode of partitioning between a flowing mobile phase and a stationary phase. In the natural gas industry gas chromatographs are widely used because of the complex chemical composition of the gas mixture. The operator collects the gas from the gas field, saves it in the gas storage tank, and then determines the gas composition and the concentration via the column chromatographic separation technique in the laboratory. [7] The main working principle of the gas chromatographs is to separate all the gas components into columns and process every gas individually with detectors. With the measured fractions of each component, gas chromatographs calculate the desired gas quality parameters such as relative density, wobbe index and calorific value. Commercially available gas chromatographs are investigated and the ones which can handle hydrogen presence is given in Table 3.

Table 3 Gas chromatography devices, their producers, the mobile phase carrier, and hydrogen acceptance.

Name of the Device	Producer	Mobile Phase Carrier	Hydrogen Acceptance in Natural Gas
EnCal 3000	Elster	He	Up to 5%
PGC 9303	RMG	He	Up to 5%
PGC 9304	RMG	He and Ar	Up to 20%
SAM-Bio	Siemens/Marquis	He	Up to 3%
SAM- Complete	Siemens/Marquis	He	Up to 5%
SAM- Complete-Advance	Siemens/Marquis	He and N2	Up to 25%

Most of the gas quality instruments presented in the proceeding sections require relatively high investment and operational costs. In the natural gas sector, most of the measurement devices are based on gas chromatography. [8] There are two main disadvantages of the GC measurement technology. Firstly, it usually takes hours to get a meaningful result. Secondly, the method itself requires technically skilled operators. That is why relatively cheaper electrical sensors increased their share in the gas monitoring market. [7] Nevertheless, these sensors on its own are not suitable for gas composition analysis because of the cross sensitivity of different gases in the natural gas. Recent research and development in the optimization area have solved this problem by using artificial neural networks (ANN). It is claimed that the data can be rectified by ANN to eliminate the effect of cross-sensitivity. [8] Similarly the following researchers used different types of optimizations to measure a specific property of the gas mixture. These research and their method of optimization is given in Table 4.

Table 4 Alternative approaches of gas monitoring, their research, optimization model and used sensors.

Research	Optimization Method	Sensors	Measured Property
Areej Shahid et al.	Artificial Neural Network	SnO_2 sensor	CH_4 and CO concentration
Maria Gabriella Xibilia et al.	Deep Neural Network	Soft Sensor	Gas Concentrations
Tanghao Jia et al	Multi-layer perception neural network	Infrared Gas Sensor	Gas Concentrations

Potential Degrading of the Infrastructure

Pipelines are the safest method of transporting huge volumes of oil and gas. [9] Hydrogen transport in the existing natural gas pipeline system is proposed to increase the share of hydrogen in the energy mixture. The durability of some metal pipes can be degraded when exposed to hydrogen over a long period of time, particularly with injection at high hydrogen concentration and pressure. [10] The effect of hydrogen in the pipeline systems depends on the operating conditions and the material of the pipeline. Since REN's infrastructure of pipeline is based on various carbon steel types of API 5L B, X42, X52, X60, X70 this chapter focuses on the hydrogen effect on mentioned pipeline steel.

Hydrogen induced failures and degradations are considered as a major integrity concern for the steel pipelines under the pressure levels of natural gas transmission and distribution. [9] Because of the nature of the operations in natural gas sector, the pipelines are continuously exposed to severe conditions.

Moreover, the combination of these conditions and diffused hydrogen in the pipeline may result in failures caused by hydrogen induced damage. [11]

It is rather easy to claim that hydrogen has a degrading effect on steel pipeline, but the limits and the condition of this degrading is an ongoing investigation for the natural gas and hydrogen sector. Therefore, the driving force behind this chapter is to introduce hydrogen degradation mechanisms and the effect of increased hydrogen levels in the system.

Boukart measured the fracture toughness of several API steel by using notched Roman tile specimens. In the experiment procedure same measurement are repeated with electrolytic hydrogen charging. The fracture is compared before and after hydrogen charging. According to this comparison hydrogen-air fracture toughness ratio as a function of yield strength decreased approximately by 33%. This decrease is observed in API X52 and X70 pipeline steel. Figure 2. shows the difference in the elongation at the rapture caused by hydrogen embrittlement effect. [10]

Similarly, many researchers have experimented on the topic. For example, Capelle et all investigated the hydrogen effect on API X52, X70 and X100 with Roman tile specimens. According to a set of experiments fracture toughness decreased for X52 and X70 steel pipeline by 10.46% and 4.74% respectively.[9] The change in the fracture toughness can be observed from Capelle er al.'s graph which is shown in Figure 3.

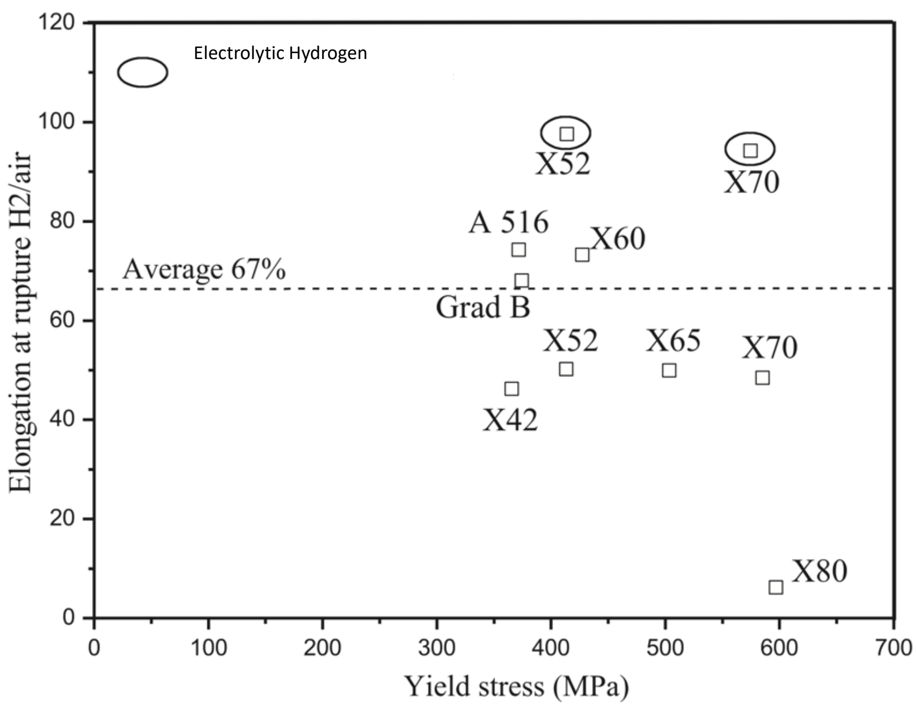

Figure 2 Effect of hydrogen embrittlement in the fracture toughness as a function of yield strength.[10]

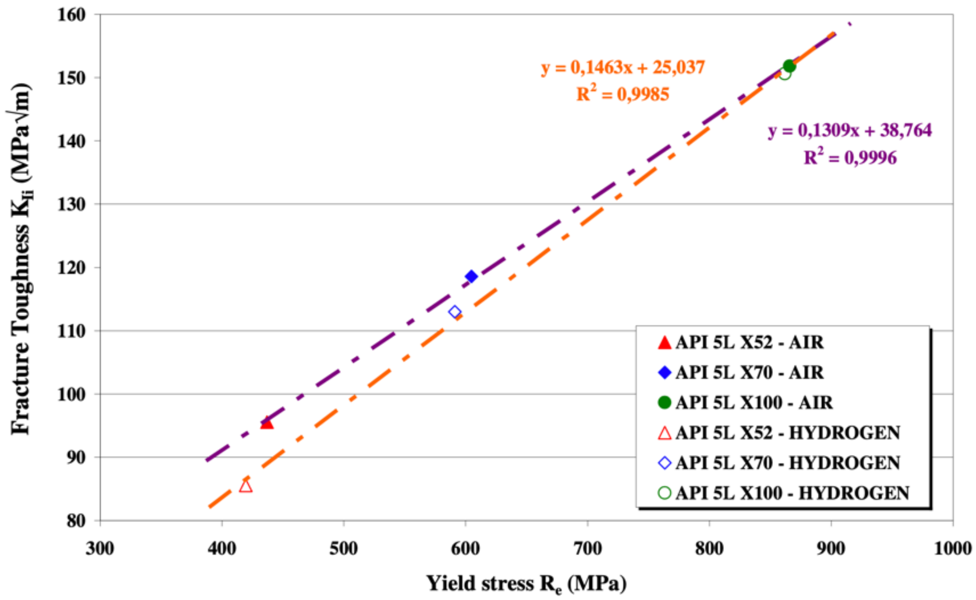

Figure 3 The change in fracture toughness of API 5 L X52, X70 and X100 pipeline steels in hydrogen charging.[9]

Meliani et al. experimented on API 5L steels with different types of specimens. (SENT, CT, DCB, and Roman tile). As a result of this study a material failure curve based on the critical notch intensity factor is plotted.[12] As an experimental approach, all the specimens are exposed to hydrogen charging for 30 days. Typically, the results for Roman tile specimen are the focus of this thesis because of its pipeline like shape. According to the research, because of the presence of hydrogen charging the notch stress intensity factor decreases 9.8% compared to the control specimen of API 5L X52 steel.[12] The difference in the notch stress intensity factor due to hydrogen charging is shown in Figure 4.

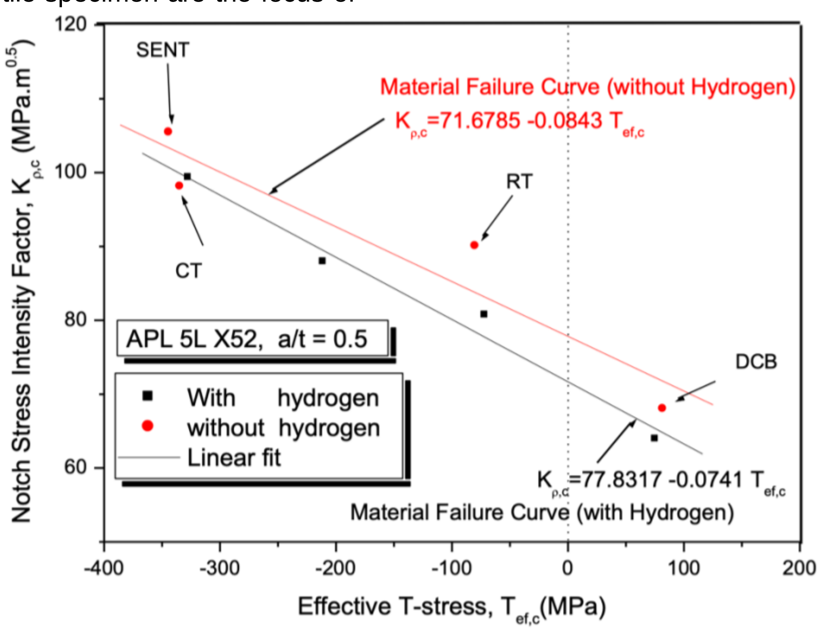

Figure 4 The change in notch stress intensity factor because of hydrogen charging.[12]

Conclusion

The development of laws and policies against the greenhouse gases has increased the importance of carbon free energy solutions in the world. Hydrogen has a high potential of being the primer force in this energy transition because of its low carbon nature and its wide range of applications. It is known that hydrogen can be utilized in energy production, energy storage, transportation as a fuel and heat source for many industries. However, one of the most interesting utilization methods of hydrogen is the injection to natural gas networks. Transportation cost of hydrogen in pressurized vessels are genuinely high, that is why hydrogen transportation and usage in natural gas industry is proposed as a solution.

Many of the member states in European Union started investing on hydrogen production and utilization methods because current policies of European Commission promote the green hydrogen economy. In case of hydrogen injection into natural gas network many countries still investigate the possible outcomes of such application while some countries like France, Germany and Spain allow significant percentages of hydrogen in their system. With development of the new hydrogen strategy Portugal aims to be one of the countries which injects hydrogen in their transmission system up to 5% by 2025 10% by 2028 and by 15% by 2030. REN as the main TSO in Portugal will play a key role in this energy transition process. The principal responsibility of REN will be receiving hydrogen from producers and blend it to the natural gas mixture. While producers are building the connection to natural gas REN will supervise and control the sustainability and the durability of the hydrogen injection into the network. There are several projects all around the world which proves that regular natural gas networks can handle 10% hydrogen in the system with minor operations. These projects are HyDeploy by U.K., Snam by Italy, Dunkirk by France, and HyBlend by U.S.A.

Although, it is proven by several research and development projects hydrogen injection is possible up to 20% with minor adaptations, the changes in the system cannot be ignored. In the chapter 4 these changes are analyzed and calculated.

As it can be seen in Table 5. most of the changes are related with natural gas quality. Therefore, gas quality monitoring has a critical importance. Because of this reason, gas quality monitoring methods, equipment and new approaches are investigated under Chapter 5. Gas chromatographs which has hydrogen tolerance are presented and suggested. Additionally, because of the high capital cost of conventional gas chromatographs the usage of relatively cheaper gas sensors and application of artificial neural network method is investigated and suggested for increasing hydrogen volumes in the gas mixture.
Finally, one of the biggest concerns in the natural gas industry which is possible degradations due to hydrogen content is studied under Chapter 6. The hydrogen embrittlement and its modes are given and their degrading effect on REN's pipeline infrastructure is discussed. From literature, experiments including roman tile specimens are selected and hydrogen's negative effect on the mechanical properties of carbon steel pipeline is presented.

To conclude, hydrogen blending with natural gas will technically be feasible with minor adjustments in the current infrastructure for blends which has less than 10% hydrogen. If the hydrogen percentage exceeds this limit additional research and adaptations will be required especially for hydrogen degrading effect and gas quality monitoring. For the first years of the project the main investment for REN will be building the blending station and designing the blending equipment for large quantities of natural gas and hydrogen blend.

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