Power Losses in Natural Gas and Hydrogen Transmission in the Portuguese High-Pressure Network

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Abstract

Nowadays, along with climate emergency, energy shortage is a challenge being faced worldwide. For such, energy savings play an essential role, for example, by improving energy efficiencies. Transporting natural gas inside pipelines has associated power losses. In this context, the Dissertation focuses on developing a computational tool representing the Portuguese high-pressure gas network supplying Portuguese industrial consumers. This tool computes the mass flow rate required by each industry and the power losses associated with its supply. Several scenarios are defined and supplying the Portuguese industry from Sines has a power loss of 4.21%. The exportation to Spain has fewer power losses when divided through Campo Maior and Valença. Filling Carriço Underground Storage has higher power losses associated, but it is advantageous to use the gas stored to later supply the industry. Power losses increase when hydrogen is added in the mixture, and a linear correlation is developed for 0 to 20% of hydrogen in volume. An economic assessment is conducted for producing hydrogen, and Levelised Cost of Hydrogen, Net Present Value, Internal Rate of Return, and Payback Period are 4.99 €/kg, 242.79 M€, 21%, and 5 years, respectively. The Net Present Value is positive for all scenarios, being most sensitive to hydrogen selling and electricity prices. The economic impact on the industry is highly sensitive to the prices considered.

Keywords: Power Loss, Pipeline, Natural Gas, Hydrogen, Portuguese Natural Gas Transmission Network, Economic Assessment

1. Introduction

Nowadays, climate emergency is one of the most concerning challenges being faced worldwide. The greenhouse gases (GHG) emissions to the atmosphere, allied with energy dependence on fossil fuels have aggravated this environmental crisis. Urgent measures must be implemented to reverse the situation that all nations find themselves in.

Another challenge being faced is the energy shortage [1]. The supply of natural gas (NG) and other energy sources is insufficient to satisfy demand, and, as a result, the planet is undergoing through an energy crisis. This problem has been aggravated by the interruption of gas supply from Russia, and it will become even worsened by the eventual run-out of reserves [2]. The most effective method to address the energy shortages is to save energy rather than generate more [3]. In this context, energy saving means decreasing the energy consumption of a unit product, which is to improve energy efficiency.

Presently, NG is one of the most consumed types of fuel worldwide, along with coal and oil [4]. When NG is burned to generate electricity, it emits around half of the quantity of CO_2 compared to coal [5]. Therefore, NG has shown significant potential in minimizing near-term carbon dioxide (CO_2) emissions. Despite all these advantages, the exclusive usage of NG is no longer viable since the ultimate objective is to cease the emission of pollutant substances and to suspend the dependency on non-renewable energy sources. However, the NG cessation must be effectuated continuously to slowly decarbonise the economies since the global market is still immensely dependent on NG.

The supply of NG is usually executed through pipelines. Transporting a fluid in pipelines has an associated power loss that includes both viscous frictional losses and losses due to heat transfer along the pipe. The viscous friction established between the fluid particles and walls is responsible for some energy dissipation when fluid travels in a pipe. This loss due to friction causes a pressure drop along the length of the pipe, therefore increasing the amount of power that a pump must deliver to maintain the flow. This pressure drop depends on parameters such as, cross-section, length, flow rate, material, roughness, and the fluid itself. Sletfjerding and Gudmundsson [6] elaborated a new friction factor correlation in terms of direct measurement of roughness. Given the relevance of the frictional loss parameter, Huang *et al.* analysed the effect of using drag reduction agent (DRA) technology on the pipe inner-surface roughness, and article by Ma *et al.* [7] synthesised a new DRA named organic carboxylate polymer (CPA) to reduce the roughness effect on the NG pipe. On the other hand, there are mainly two mechanisms of heat transfer in pipelines. The first is conduction, which occurs when there is a thermal path between areas with different temperatures. The other is convection, which results from fluid motion over a thermally active surface.

Modelling gas transmission networks in computational tools is a topic being recently developed [8, 9, 10]. Through these developments, more investigations can be effectuated to implement improvements in gas networks. It is important to mention that the case of modelling a country's high-pressure gas network, which is the topic being studied in this work, has not been investigated as far as the Author is aware.

Another promising concept through a more sustainable path is the usage of hydrogen (H_2) as an alternative fuel. Electrolysis can be a prospective process for producing green H_2 if produced from renewable resources using electrolysers. The most frequently used include alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), and solid oxide electrolysis (SOEL). To exemplify, the AEL produces H_2 in assembled cells composed of an anode, a cathode, and a membrane. The principle of operation of AEL is the movement of hydroxide ions through the electrolyte from the cathode to the anode, generating H_2 on the cathode side and oxygen (O_2) on the anode side.

Given the potential of H_2 to start to decarbonise the NG network, the impact of blending H_2 in the NG pipelines should be well-known, particularly the effect on the thermo-physical properties of the NG. Schouten *et al.* [11] concluded that the energy density decreased when H_2 is added. The pressure gradient in the pipelines is larger when NG is transported compared to the mixture containing H_2 if the same quantity of gas is transported on a volumetric basis. However, the opposite was verified if the same amount of gas is transported on the same energy basis instead of volumetric. Deymi-Dashtebayaz *et al.* [12] verified that adding H_2 increased the upper and lower flammability limits, lower heating value (LHV), higher heating value (HHV), and compressibility factor, and decreased the Wobbe indices and density.

Pipelines are the most cost-effective, energy-efficient, and safest way to transport H_2 over long distances [13]. The current lack of H_2 infrastructure is a significant barrier to the widespread use of H_2. There are proposals to inject H_2 into the existing NG grid, allowing for a faster and more cost-effective transition to H_2 transport [14, 15]. Gondal *et al.* [16] stated that each element in the infrastructure has its own capability of accepting different H_2 concentrations.

Moreover, the economic viability of producing such H_2 through electrolysis is reviewed. Schmidt *et al.* [17] predicted that the electrolyser capital cost is able to reduce by 0–24%. Nguyen *et al.* [18] performed a techno-economic analysis in a large-scale H_2 production plant, resulting in a Levelised Cost of Hydrogen (LCOH) of $3 - 3.3$ €/kg for AEL. The work of Minutillo *et al.* [19] focused on a techno-economic assessment in refueling stations with H_2 electrolysis and the project's LCOH ranged from $9.29 - 12.48$ €/kg.

The main objective of the present Dissertation is to analyse the power losses associated with the transmission of natural gas and hydrogen in the Portuguese high-pressure network. Particularly, this work aims to create and validate the computational tool which computes the required mass flow rate to answer the energy demand of the Portuguese major industrial consumers as well as the power losses associated to its transmission. For such, scenarios within the Portuguese Natural Gas Transmission Network (RNTGN) are defined to comprise several supply options, and the power losses associated to the NG transmission to supply the Portuguese industrial consumers for the defined scenarios are computed. Afterwards, the influence of blending several percentages of H_2 in the NG mixture on the power losses for the same scenarios is analysed. Finally, the economic viability of producing the H_2 to be blended in the NG mixture is studied, as well as the economic impact in the industries of using the mixture with those several percentages of H_2. Essentially, this work aspires to assist the beginning of the decarbonisation path in the Portuguese network. Even though this work does not present the complete solution to cease the dependence on natural gas, it contemplates mixtures with small percentages of hydrogen to start to understand further implications of future usage of the Portuguese network to transport exclusively hydrogen, such as the power losses associated with its transmission.

2. Theoretical Background

This section presents the governing equations incorporated in the numerical model.

The energy balance is presented in Equation (1), which establishes a corresponding between the dynamics of pressure and temperature of the internal representing the gas volume and the energy and heat flow rates. The term $\frac{\partial U}{\partial p}$ is the partial derivative of internal energy of the gas volume with regard to the pressure at constant temperature and volume, $\frac{\partial U}{\partial T}$ regards the temperature at constant pressure and volume, Φ_{in} [W] and Φ_{out} [W] are energy flows at the inlet and outlet, and q_{sur} [W] is the heat flow rate from the surroundings.

$$\frac{\partial U}{\partial p} \cdot \frac{dp_{\text{I}}}{dt} + \frac{\partial U}{\partial T} \cdot \frac{dT_{\text{I}}}{dt} = \Phi_{\text{in}} + \Phi_{\text{out}} + q_{\text{sur}} \tag{1}$$

The momentum balance written in Equation (2) is known as Bernoulli's Equation, though not considering the gravitational potential energy term. The pressure drop caused by momentum flux and viscous friction is described for the first half of the pipe. The equation for the second half of the pipe is similar. The terms p [MPa] and ρ [kg/m^3] are the pressure and density at inlet, outlet, or internal node, as indicated by each subscript, and the term S is the pipe cross-sectional area. The terms $\Delta p_{\text{in,I}}$ and $\Delta p_{\text{out,I}}$ are the pressures losses due to viscous friction.

$$p_{\text{in}} - p_{\text{I}} = \left(\frac{\dot{m}_{\text{in}}}{S}\right)^2 \cdot \left(\frac{1}{\rho_{\text{I}}} - \frac{1}{\rho_{\text{in}}}\right) + \Delta p_{\text{in,I}} \tag{2}$$

The calculation of the pressure losses due to viscous friction depends on the flow regime, hence, the Reynolds number on both halves of the pipe must be computed. For the flow circulating inside the pipe on turbulent flow regime, the pressure losses caused by viscous friction are determined using Equation (3). The Darcy factor is calculated using Haaland correlation.

$$\Delta p_{\text{in,I}_{\text{turb}}} = f_{\text{Darcy}_{\text{in}}} \frac{\dot{m}_{\text{in}} \cdot |\dot{m}_{\text{in}}|}{2\rho_{\text{I}} \cdot D_{\text{hyd}} \cdot S^2} \cdot \frac{L + L_{\text{eqv}}}{2} \tag{3}$$

On the other hand, the convective heat transfer equation between the internal gas volume and the pipe wall is presented in Equation (4).

$$q_{\text{sur}} = q_{\text{cond}} + q_{\text{conv}} \tag{4}$$

The conductive heat transfer is calculated with Equation (5), where $S_{\text{surf}} = \frac{4SL}{D_{\text{hyd}}}$ [m^2] is the pipe surface area and k [W/m $\cdot$ K] is the thermal conductivity. The convective heat transfer term h [J/kg] is computed considering an exponential distribution along the pipe, as in Equation (6), where $\dot{m}_{\text{avg}}$ [kg/s] is the average mass flow rate between the pipe's inlet and outlet, and the term $c_{\text{p}_{\text{avg}}}$ [J/kg $\cdot$ K] is the specific heat evaluated at the average temperature. The heat transfer coefficient depends on the Nusselt number that is determined through Gnielinski correlation for turbulent flow.

$$q_{\text{cond}} = \frac{k_{\text{I}} S_{\text{surf}}}{D_{\text{hyd}}} \left(T_{\text{sur}} - T_{\text{I}}\right) \tag{5}$$

$$\begin{aligned} q_{\text{conv}} &= |\dot{m}_{\text{avg}}|\, c_{\text{p}_{\text{avg}}} \left(T_{\text{sur}} - T_{\text{in}}\right) \\ &\left(1 - \exp\left(-\frac{h S_{\text{surf}}}{|\dot{m}_{\text{avg}}|\, c_{\text{p}_{\text{avg}}}}\right)\right) \end{aligned} \tag{6}$$

3. Implementation

The numerical model is developed with the aim of computing the power loss inside a pipeline transporting NG. This model developed in Simulink is the core of the computational tool created in MATLAB-Simulink. The case of study addresses the supply of those industries through the RNTGN, and the objective is to compute the required NG mass flow rate to satisfy the demand of the Portuguese major industrial consumers, as well as the power losses associated with its transmission. The list of the CO_2-emitting Portuguese industry taken into consideration in the model is from [20], which presents the amount of CO_2 that each one emits gratuitously in a year. The simplification of NG being constituted by 100% of methane (CH_4) is assumed. Therefore, the required mass flow rate to satisfy the demand of each industry is computed using the number of licenses.

In the computational tool, the RNTGN is divided into several pipeline segments [21], as presented in Table 1.

Table 1: RNTGN pipeline segments considered in the computational tool, from [21].

Segment	D_{hyd} [m]	L [km]
Sines – Setúbal	0.8	87
Setúbal – Bidoeira	0.7	174
Bidoeira – Campo Maior	0.7	220
Bidoeira – Figueira da Foz	0.7	19
Bidoeira – Cantanhede	0.7	64
Cantanhede – Mangualde	0.5	68
Mangualde – Celorico	0.7	48
Celorico – Guarda	0.3	29
Guarda – Monforte	0.3	184
Cantanhede – Gondomar	0.7	100
Gondomar – Braga	0.5	50
Braga – Valença do Minho	0.7	100

Every industry is connected to the nearest segment of the main pipeline through ramifications, which transport the mass flow rate necessary to feed the respective demand. The computational tool considers the NG mass flow rate input in the Liquified Natural Gas (LNG) Terminal at Sines. Followingly, all the segments are interconnected in the correct geographical order through a MATLAB program. The mass flow rate input of the following segment is equal to the output of the previous segment, which means that the program always considers the remaining mass flow rate from the principal pipeline since a certain amount exited through ramifications to the respective industries.

The main aim is to compute the power losses. The overall power loss is computed through an energy balance that considers as input the mass flow rate entering the segment Sines-Setúbal with the quantity required to feed the Portuguese major industrial consumers, as well as the power provided by the mass flow rate source and the minor difference at the segments interconnection. The output considers all the powers measured at the end of each ramification of the segments, as well as the residual remaining exiting mass flow rate at the end of the last segment.

The developed computational tool is also applied for NG blended with several percentages of H_2: $5\%_{vol}$, $10\%_{vol}$, and $20\%_{vol}$ of H_2. However, when introducing H_2, the mass flow rate required to satisfy the Portuguese industrial consumers is inferior for the same energy, since the LHV of H_2 is superior compared to the LHV of CH_4. Essentially, the aim is to compare the power losses in the transmission of NG and of NG blended with H_2, to directly understand the impact of this blend.

4. Results and Discussion

Firstly, the developed numerical model is validated. Then, the case of study is defined, where a power losses study is effectuated, followed by a study about the influence of blending H_2, an economic assessment from the perspective of the H_2 producer, and a study about the economic impact on the industry.

4.1. Model Validation

The model developed in MATLAB-Simulink is validated through a comparison with the work done by Schouten *et al.* in 2004 [11]. The results regarding the pressure drop inside the pipeline obtained with the model are compared for a practical example, which consists of a pipeline with 90 km and a hydraulic diameter of 1.04 m. The considered mixtures are a lean gas with the composition referred in [11] as well as the same lean gas mixed with $25\%_{mol}$ of H_2. The simulations are conducted with the data according to the mentioned work, which is summarized in Table 2. The schematic representation of the model is depicted in Figure 1.

Table 2: Validation data from [11].

T [K]	p [MPa]	$\varepsilon \cdot 10^{-6}$ [m]	$\mu \cdot 10^{-6}$ [Pa.s]	Q [m^3/s]
280	6.5	12	12	425

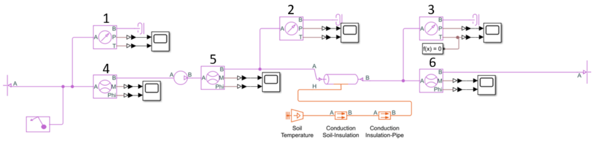

Figure 1: Schematic of the simplified model in MATLAB-Simulink with the sensors enumerated.

The results obtained are presented in Table 3. It is important to emphasize that these simulations were performed with the same amount of gas being transported within the two gaseous mixtures on a volumetric basis.

Table 3: Pressure drop (PD) on the transmission of NG mixture and blended with $25\%_{mol}$ of H_2 on the same volumetric basis.

	p_2 [MPa]	p_3 [MPa]	PD [MPa]	PD from [11] [MPa]
100% Mix. of [11]	7.692	6.5	1.192	1.190
25% H_2	7.487	6.5	0.987	0.990

For both transmission of NG and NG blended with $25\%_{mol}$ of H_2, the computed pressure drops are similar to the values obtained in [11], which demonstrates a good agreement between the results of the developed model and the ones of considered work. Thusly, the developed model is then concluded to be validated.

On the other hand, the simulations are conducted considering the same amount of gas being transported on an energy basis. Therefore, the results of Table 4 are attained.

Table 4: Pressure drop (PD) on the transmission of NG mixture and blended with $25\%_{mol}$ of H_2 on the same energy basis.

	p_2 [MPa]	p_3 [MPa]	PD [MPa]
100% Mix. of [11]	7.692	6.5	1.192
25% H_2	7.917	6.5	1.417

The pressure drops are larger for the case of the admixture of NG and H_2 compared to the case of only NG, as also concluded in [11]. Hence, the pressure drop in the pipelines is lesser in the case of NG than in the mixture containing H_2 when the same gas quantity is transported on an energy basis, however it is greater on a volumetric basis. This occurs since, when transporting the same gas quantity with H_2 on a volumetric basis, the correspondent mass flow rate is inferior than when transporting the same gas quantity with H_2 on an energy basis, leading to a lower pressure drop. On the other side, when comparing the case of transporting only NG with the case of the same gas quantity of NG and H_2 on an energy basis, despite the mass flow rate being superior transporting only NG, due to the different inherent gas properties, as it is discussed further, the pressure drop is superior for the case with H_2.

The power of gas flow can also be measured through Sensors 5 and 6 placed in the model, as observed in Figure 1. Thus, it is possible to compute the efficiency and power losses of the transmission system. For such, the case of transporting the same amount of gas on an energy basis is once more considered, and the results of Table 5 are obtained.

Table 5: Power losses (PL) on the transmission of NG mixture and blended with $25\%_{\mathrm{mol}}$ of H_2 on the same energy basis.

	% Efficiency	% PL
100% Mix. of [11]	86.77	13.23
25% H_2	83.75	16.25

By observing the results of Table 5, the efficiency in the transmission computed through the power measurements is lower for the case with H_2 blended in the mixture than in the case without. This means that the transmission of the admixture of NG with H_2 has more power losses associated. When both Table 4 and Table 5 are compared, it can also be discerned that larger pressure drops correspond to higher power losses in the pipeline.

4.2. Case of Study

The created computational tool models the case of study, which consists of the entire RNTGN supplying the Portuguese major industrial consumers with the NG mass flow rate necessary to feed its demand. The main objective is to determine the percentage of power losses associated with the transmission of the mass flow rate through the trajectory inside the pipelines until arriving to each industry. With the aim of assessing these power losses, the case of study includes different supply scenarios, for which the results are obtained for the transmission of NG in the RNTGN. The considered scenarios are the following:

(A) Industrial Supply Scenario: LNG Terminal at Sines supplying the Portuguese major industrial consumers;

(B) Exportation Scenario: LNG Terminal at Sines supplying the Portuguese major industrial consumers and exporting 10% to Spain;

(C) Storage Scenario: LNG Terminal at Sines supplying the Portuguese major industrial consumers and filling the caverns of Carriço Underground Gas Storage; and

(D) Industrial Supply from Storage Scenario: Carriço Underground Gas Storage and LNG Terminal at Sines supplying the Portuguese major industrial consumers.

4.2.1 Power Losses Study

For Scenario (A), an annual energy supply of 41.97 TWh is required to satisfy the demand of the Portuguese major industrial consumers, which translates on a NG mass flow rate of 95.74 kg/s that is provided from the LNG Terminal at Sines. Regarding the Scenario (B), the Portuguese industry stands in need for the same energy, and the energy to be exported is an extra 4.20 TWh. This scenario contemplates three exportation possibilities, which include the exportation fully through Valença do Minho (B.1), fully through Campo Maior (B.2), and divided through both at the same time (B.3). The total NG mass flow rate is inputted at Sines. For Scenario (C), the caverns of Carriço Underground Gas Storage are filled as the same time as the Portuguese industrial consumers are fed, all with NG supplied from LNG Terminal at Sines. However, the caverns' maximum injection capability is restrained to 2 Mm^3/day [22], which limits the amount of NG that can be introduced *per* second (C.1). This scenario also contemplates the hypothetical case of this injection capability being doubled up to 4 Mm^3/day (C.2). Scenario (D) comprises the extraction of NG from Carriço Underground Gas Storage. Since the caverns' maximum extraction capability is limited to 7.2 Mm^3/day [22], which is insufficient to satisfy the whole demand, the supply from LNG Terminal at Sines is necessary to provide the remaining quantity. Hence, the aforementioned scenarios are applied in the developed computational tool and the results of the power losses associated to the NG transmission are obtained. These results are presented in Table 6.

Table 6: Power losses (PL) results with regard to NG transmission for all scenarios.

	(A)	(B.1)	(B.2)	(B.3)	(C.1)	(C.2)	(D)
% PL	4.21	5.27	5.23	5.18	6.00	7.98	3.22

Firstly, the power loss associated with the NG transmission of Scenario (A) is 4.21%. Secondly, the power losses of Scenarios (B.1), (B.2), and (B.3) are 5.27%, 5.23%, and 5.18%, respectively. Since the mass flow rate is inputted in the LNG Terminal at Sines for these scenarios, the distance from Sines to these exportation locations should be emphasised. Given that the pressure drop due to viscous friction is a strong component that influences the power losses, this relationship highly affects the results. Longer pipelines imply higher pressure drops when the NG is transported since, as enlightened by Equation (3). Therefore, since Campo Maior is closer to Sines compared to Valença do Minho, this explains the power losses of Scenario (B.1) – 5.27% – being larger than the power losses of Scenario (B.2) – 5.23%. Besides, the increase of the mass flow rate entering the pipeline implies an increase of the associated power losses, for the same reason as previously, which explains the power loss result for the Scenario (B.3) of 5.18%, due to the fact that this scenario considers the division of the mass flow rate to be exported into both locations. Therefore, there is less quantity of mass flow rate going through the pipeline segments to each direction, despite the distance from Sines to Valença do Minho being superior. Consequently, Scenario (B.3) is the most interesting exportation scenario, since the power loss associated is the lowest among the three exportation options.

Thirdly, Scenarios (C.1) and (C.2) present power losses of 6.00% and 7.98%. In terms of travelled distances inside the pipelines, both Scenarios (C.1) and (C.2) are similar, and the only difference relies on the amount of NG mass flow rate being transported inside the pipelines. Scenario (C.2) requires more mass flow rate circulating inside the RNTGN than Scenario (C.1). Since the power loss of Scenario (C.2) – 7.98% – is higher than the power loss of Scenario (C.1) – 6.00% –, it corroborates with a superior mass flow rate circulating inside a pipe having a larger power loss related to its transmission.

Regarding Scenario (D), the power losses are 3.22%. This scenario presents the lowest percentage of power loss of all the considered scenarios, which is attributable to two contributions. To begin with, there is less distance to be travelled by the NG inside the pipelines considering that there are two sources of NG input into the network (Sines and Carriço). Moreover, there is less mass flow rate in the segments for the same reason. Therefore, the power loss associated with this scenario is the lowest.

One can conclude that it is advantageous to use the NG stored inside the salt caverns of Carriço to feed the demand of the Portuguese industrial sector in terms of power losses. However, the fill of these caverns has its own associated power losses. A beneficial strategy could be to fill in the caverns in periods where the industrial demand is not at its peak, for example, at night. Another possible strategy to better exploit the results could be to build more salt caverns distributed along the territory. This would have less power losses associated with both its filling and its usage to satisfy the NG demand from the industry.

4.2.2 Influence of Hydrogen

The computational tool also computes the results for several percentages of H_2, to be compared to the case of transmission of NG without H_2 in the mixture, for the same scenarios. The industry requires the same amount of energy, since LHV of H_2 is higher than LHV of CH_4, the required mass flow rate is inferior compared to the case of transporting only NG. Accordingly, the results of Table 7 are attained.

Table 7: Power losses (PL) results for Scenario (A) with regard to transmission of the admixture with several percentages of H_2.

	100% NG	5% H_2	10% H_2	20% H_2
% PL	4.21	4.86	5.44	6.83

The higher the percentage of H_2 in the mixture, more power losses are associated with its transmission. It can be explained by the change of the mixture properties when adding more H_2, since the mixture density is severely affected by the H_2 addition, decreasing considerably. When the mixture density decreases, the pressure drop due to viscous friction increases, increasing the power loss. Another explanation relies on power losses also being influenced by the losses due to heat transfer along the pipe. When H_2 is added, the thermal conductivity of the mixture increases considerably, increasing the heat transfer through conduction, hence, higher power losses.

When analysing the obtained results from Scenario (A), they evidence a linear trend. A linear regression can be computed to estimate the percentage of power losses obtained by transporting mixtures with different percentages of H_2. The plot of Figure 2 shows the performed linear regression and the developed correlation to calculate the power losses, which is also written in Equation (7), for a percentage of hydrogen between 0 - 20% present in the mixture.

$$\%\text{Power losses} = 0.1295 \cdot \%\text{H}_2 + 4.21 \tag{7}$$

This correlation can be extended to be also employed for the other scenarios. The only modification that needs to be made is the replacement of the value 4.21%, by the value of the power loss transporting only NG in the respective scenario. The general correlation is written in Equation (8), where b is the percentage of power loss of transporting only NG for the respective scenario.

$$\%\text{Power losses} = 0.1295 \cdot \%\text{H}_2 + \text{b} \tag{8}$$

Therefore, Table 8 shows the obtained power losses computed through this correlation for every

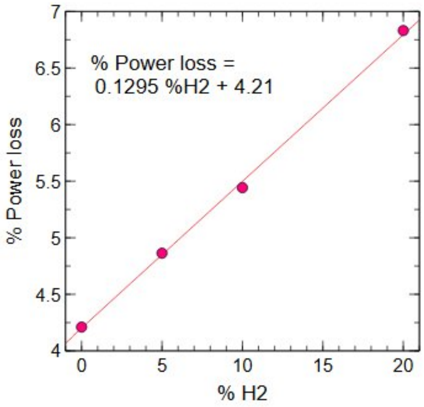

Figure 2: Linear regression for percentage of power loss as a function of the percentage of H_2 in the mixture for Scenario (A).

scenario, for a percentage of hydrogen between 0 - 20% present in the mixture.

Table 8: Power losses of transmission of several percentages of H_2 for all scenarios.

	(A)	(B.1)	(B.2)	(B.3)	(C.1)	(C.2)	(D)
100% NG	4.21	5.27	5.23	5.18	6.00	7.98	3.22
5% H_2	4.86	5.92	5.88	5.83	6.64	8.63	3.87
10% H_2	5.44	6.57	6.53	6.48	7.29	9.27	4.52
20% H_2	6.83	7.86	7.82	7.77	8.59	10.57	5.81

4.2.3 Economic Assessment of Hydrogen Production

The economic assessment for a H_2 production project is performed in the perspective of a private H_2 producer located in Sines, contemplating exclusively the production of H_2, which means that this study does not regard costs of the transmission and storage in the RNTGN since the same infrastructure is used. The power losses related to its transmission computed through the developed computational tool are incorporated in this economic model in the sense that, by considering the production of the H_2 quantity required to feed the Portuguese major industrial consumers, it is also produced the extra amount related to the power loss, so the industry receive the exactly demanded energy.

The base case parameters considered include a rate of return on investment r equal to 8%, income tax of 20%, electrolyser input power of 47 kWh, lifetime of 20 years, capital expenditures (CAPEX) of 1600 €/kW, operational expenditures (OPEX) equal to 3% of CAPEX, electricity price of 0.08 €/kWh, and a water price of 1.65 €/m^3. For the Net Present Value (NPV) computation, the sales of both H_2 and O_2 are accounted with prices of 5 €/kg, for H_2, and 0.1 €/kg and 0.7 €/kg, for industrial and medical O_2.

The LCOH value of 4.99 €/kg_{H_2} is determined. The computed NPV for Scenario (A) with 5% of H_2 is 242.79 M€, which characterizes a economically viable project. The Internal Rate of Return (IRR) is 21% and the Payback Period (PBP) is approximately 5 years. Furthermore, all the H_2 production projects to supply every scenario, that comprise transporting a mixture with 5% of H_2, have a positive NPV, and it is greater when more quantity of H_2 is produced.

Some of the parameters considered in the calculation of the economic indicators can vary, for such, a sensitivity analysis on the NPV is performed, in which the influence of a few variables is analysed. All the variables are varied from −100% to +100% of the respective base value.

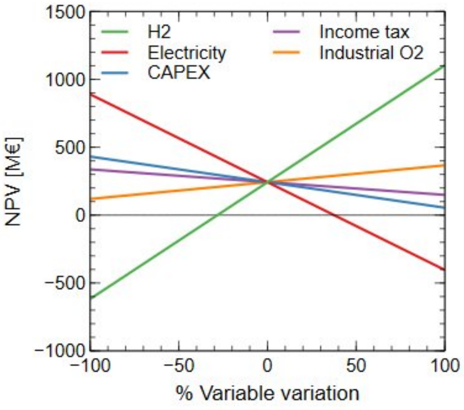

Figure 3: Combined sensitivity analysis of NPV [M€] as a function of all variables being varied from −100% to +100% of the respective base value, for Scenario (A) with 5% of H_2.

From this combined sensitivity analysis, one can conclude that the NPV is more sensitive to the H_2 selling price and the electricity price, but with opposite effects. While the NPV sharply decreases with the increase of the electricity price, it sharply grows with the increase of the H_2 selling price. The NPV turns out negative, and the project becomes economically non-viable, when the H_2 selling price decreases to lower than 3.59 €/kg and when the electricity prices rises over 0.11 €/kWh. When the other considered variables are varied from −100% to +100%, the project's NPV remains positive. However, it can still be concluded that the NPV is more sensitive to the CAPEX variation, followed by the industrial O_2 selling price, and finally by the income tax rate. The effect of increasing the industrial O_2 selling price on the NPV is contrary to the CAPEX and the income tax rate, since the sales of industrial O_2 are a revenue while the CAPEX and the income tax rate are expenses.

The previous analysis just contemplates a single scenario, however, the only difference between the various mixture compositions relies exclusively on the quantity of produced H_2. This implies that more quantity of H_2 has to be produced in the electrolyser, to compensate both for the higher percentage of H_2 present in the mixture as well as for the power that is lost when it is transported.

The project's NPV as a function of the percentage of H_2 contained in the mixture that is transported to feed the energy necessities of Scenario (A) is represented in the plot of Figure 4.

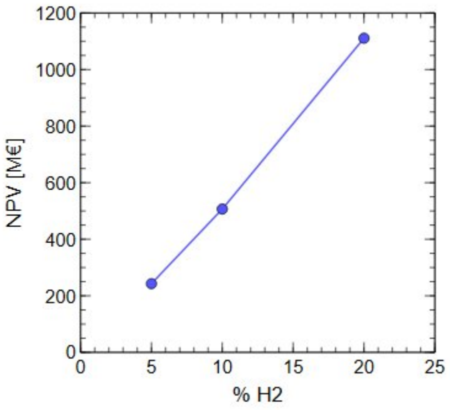

Figure 4: NPV [M€] as a function of the percentage of H_2 contained in the mixture that is transported to feed the energy necessities of Scenario (A).

It can be observed that the trend line is not linear, which coheres with what is explained above. A larger H_2 percentage in the mixture demands more quantity of H_2 produced not only by the greater presence in the mixture but also due to the more considerable power losses in its transmission through the pipelines. Since more quantity of H_2 is produced in the electrolyser, the revenue related to H_2 and O_2 sales is greater. Therefore, increasing the percentage of H_2 in the mixture also increases the NPV growth rate.

4.2.4 Economic Impact in the Industry

This analysis has the objective of studying if the industries save capital when using NG blended with various percentages of H_2. The attributed CO_2 licenses will not be cost–free beyond 2030 [20]. By burning a mixture of NG with H_2, less CO_2 is emitted to the atmosphere, and an inferior number of licenses need to be purchased. However, the price of H_2 is higher than of NG. For this study, the chosen company is a ceramic industry named C.S. Coelho da Silva. Considering a NG price of 120 €/MWh and a CO_2 license price of 67 €/ton_{CO_2}, the industry spends 10.81 M€ in NG supply to feed its energy necessities and a total 1.19 M€ related to the purchased licenses to emit CO_2. Therefore, the addition of this new component only involves a reduction of the number of bought CO_2 permits and purchasing the gas fuel composed by NG and H_2, with a H_2 price of 5 €/kg.

Table 9 shows the net licenses cost, net fuel cost, and net income, for all mixtures with several percentages of H_2. The net license cost results from the difference of the CO_2 licenses purchased for burning only NG and licenses purchased for the mixture with H_2. The usage of the new mixture composition reduces the CO_2 emissions by 1.54%, 3.19%, and 6.90%, for 5%, 10%, and 20% of H_2, respectively. The net fuel cost is obtained through the difference of cost of the fuel bought to satisfy the industry demand in the case of being only composed by NG and of being composed by NG and H_2. The net income refers to the difference between the net licenses cost and net fuel cost, as to understand if adding H_2 benefits or damages economically the industry.

Table 9: Net licenses cost and net fuel cost [k€] compared to the case of 100% of NG, and respective net income [k€] for each percentage of H_2.

	Net licenses cost [k€]	Net fuel cost [k€]	Net income [k€]
5% H_2	18.36	-41.75	-23.39
10% H_2	38.06	-86.65	-48.59
20% H_2	82.28	-187.49	-105.21

By observing the results of Table 9, the net licenses cost is positive for the three H_2 percentages, which holds up to the fact that there is less CO_2 being emitted to the atmosphere. Hence, the difference of cost related to CO_2 licenses represents a saving for the industries. On the other hand, the net fuel cost is negative for all mixture compositions, meaning that it is more expensive to buy the fuel with H_2 in its composition than without, since the H_2 price is higher than of NG. Therefore, this represents an additional expense for the company. The net income is negative for the three H_2 percentages. This signifies that this fuel composition change damages the companies in the economic point of view when considering the prices assumed above.

However, the contemplated prices are extremely volatile and the variation of the these prices strongly affects the net income results. On account of the complexity to compute for what prices the industry net income is positive while fixing the remaining two, Table 10 briefly summarizes the values for which the net income turns positive. Therefore, for NG prices higher than 136.92 €/kWh, the net income grows positive, meaning that the change of mixture composition being delivered to the industry represents an economic benefit. For H_2 prices lower than 4.44 €/kg, the net income is also positive. Hence, with a H_2 price inferior to 4.44 €/kg, it is more advantageous to the industry this blend fuel composition. Finally, the net income also grows positive when the CO_2 license prices cost more than 152.68 €/ton. This means that purchasing fuel of the blend composition is more affordable than to pay for licenses to be entitled to emit CO_2 to the atmosphere.

Table 10: Prices for which the industry net income becomes positive.

	NG price [€/kWh]	H_2 price [€/kg]	CO_2 price [€/ton]
Profit	> 136.92	< 4.44	> 152.68

Thus, it is possible to have a positive economic impact on the industries since the CO_2 licenses are expected to become more expensive in the near-future, the H_2 price should decrease with the evolution of the electrolysis technology, and the NG price keeps becoming more expensive due to energy shortages.

5. Conclusions

The present work was focused on the development of a computational tool that represented the gas supply to the Portuguese major industrial consumers and computed the power losses associated through its transmission in the high-pressure network. It was validated by comparing the pressure drop inside the pipeline, and a relation with the transmission efficiency was established.

At first, the results were attained for transporting only NG. The power loss for supplying the industry from Sines – Scenario (A) – was 4.21%. For exporting to Spain – Scenarios (B.1), (B.2), and (B.3) –, their associated power losses were estimated at 5.27%, 5.23%, and 5.18%, respectively. The option of exporting from both locations at the same time was the one presenting fewer power losses, therefore it was concluded to be the most interesting alternative. The power losses of supplying the industry as well as filling the caverns of Carriço from Sines – Scenarios (C.1) and (C.2) – were determined to be 6.00% and 7.98%. The power loss associated with supplying the industry from Carriço and Sines – Scenario (D) – was computed to be 3.22%. The conclusion was that it was advantageous to use the NG stored inside the caverns to feed the Portuguese industrial demand, however, the process of filling those caverns had its own associated power losses. Therefore, it would be beneficial to fill the caverns in periods of lower industrial consumption to reduce power losses, for example, at night. Another possibility could be building more caverns distributed along the Portuguese coast to diminish the overall power losses.

Followingly, the results were attained for Scenario (A) considering H_2 in the mixture. Higher percentages of H_2 in the mixture led to more power losses associated with its transmission, and they increased linearly. A correlation was developed to estimate the power losses as a function of the percentage of H_2 in the mixture, and it could be modified to estimate for every scenario ($\%\text{Power losses} = 0.1295 \cdot \%H_2 + \text{b}$).

An economic assessment was conducted from the perspective of the H_2 producer. The LCOH was 4.99 €/kg, which is competitive for this type of project. The computed NPV was positive with a value of 242.79 M€, for producing H_2 to supply Scenario (A) with 5% of H_2. The IRR and PBP were 21% and 5 years. The NPV was also computed for the other scenarios and it more profitable when more H_2 is produced. Also, a sensitivity analysis was performed, and the H_2 selling and electricity prices were the variables that affected the NPV the most.

A specific industry was chosen to verify the impact of the change in the supplied mixture composition. The conclusion was that, in the future, the impact may be positive since the NG price continues to increase due to energy shortages, the H_2 prices are decreasing due to developments in electrolysis technologies, and the CO_2 license prices are expected to become more expensive to promote further mitigation of emissions from the industrial sector.

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