PRESERVING LINEPACK FLEXIBILITY: OPTIMIZED OPERATION OF GAS PIPELINES WITH HYDROGEN BLENDS

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ABSTRACT

Natural gas pipelines play a crucial role in the global energy landscape ensuring the efficient distribution of energy resources serving various purposes such as electricity generation, heating, and industrial processes. The objective for the forthcoming decades is to reduce natural gas consumption, with hydrogen emerging as a promising alternative energy vector. In this context, the utilisation of gas networks for hydrogen transportation represents a viable strategy to reduce emissions. Transporting energy via gas pipelines offers a distinctive advantage: the intrinsic capacity to store energy within the infrastructure itself. The gas stored in a pipeline, known as linepack, acts as short-term energy storage enabling the management of fluctuations in supply and demand or the mitigation of minor interruptions. The volumetric energy content of hydrogen is lower than that of natural gas, leading to a decrease in linepack. This study aims to investigate the viability of offsetting the linepack decrease caused by hydrogen by elevating the operating pressure of the gas pipeline and/or expanding the infrastructure. To achieve this objective, this work introduces a non-linear programming optimization approach based on an unsteady-state gas network model. The results indicate that it is possible to increase the operating pressure of the test case pipeline to offset the linepack decrease for low hydrogen blends up to 20% mol. However, for higher hydrogen concentrations, infrastructure expansion measures such as looping pipelines become necessary.

1 INTRODUCTION

Natural gas (NG), due to its lower carbon intensity compared to other fossil fuels, has been considered the fuel of transition for years (Pellegrino et al., 2017). Particularly in fully developed economies, NG played a pivotal role in displacing coal from the electricity generation sector. However, thanks to the increasing penetration of renewable energy sources, NG significance in electricity generation has diminished, leading to a decline in its consumption. Furthermore, the residential heating sector has also witnessed a reduction in NG usage, largely due to the increasing installation of heat pumps, which offer a more environmentally friendly alternative (Dodds and Demoullin, 2013). Despite these shifts, NG remains indispensable in industries requiring high-temperature heat, where electrification remains challenging in the short term (Superchi et al., 2023). Additionally, NG power plants continue to play a crucial role in stabilizing electrical networks during adverse conditions, thanks to their quick startup times. However, NG must be transported from extraction or import sites to end users. Pipelines represent the primary mode to transport NG. One significant advantage of energy transportation via pipelines lies in the inherent storage capacity of the system. Pipelines can manage supply-demand imbalances by storing or depleting gas. The amount of energy stored in a pipeline is referred to as linepack and its value characterizes the flexibility of the system (Clegg and Mancarella, 2016).

Looking ahead to the coming decades, alongside the widespread electrification of various sectors, an emerging hydrogen (H_2) economy is gaining traction (Quarton and Samsatli, 2018). H_2 serves as a promising green energy carrier, offering an alternative to NG in areas where electrification is impractical while also enabling long-term storage. However, given the significant differences in properties between H_2 and NG, researchers and industries are investigating how transporting H_2 or a blend of NG and H_2 will affect gas network operations (Quarton and Samsatli, 2020). Depending on the

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pressure level to which the network is operated, gas networks are classified as distribution or transmission networks. Even if the values change from country to country and on the application, typical pressures in distribution networks are between 1 bar_g and 10 bar_g, while transmission networks operate at pressures between 10 bar_g and 100 bar_g. The research on H_2 blending in distribution networks proposes steady-state models for tracking H_2 or simulating homogeneous blends on simplified or real networks (Cheli et al., 2021; Guzzo et al., 2024, 2022). Due to the lower pressure transient phenomena are usually negligible and the work focuses on investigating the effects on pressure losses and velocities, without considering linepack. Instead, transmission networks, operating at a higher pressure and with larger flow rates, are usually simulated with transient models and linepack playing a crucial role, is investigated. Both Quarton and Samsatli (2020), and Dodds and Demoullin (2013) agree that transporting pure H_2 in the same infrastructure will reduce more than 4 times the linepack energy value compared to NG (Dodds and Demoullin, 2013; Quarton and Samsatli, 2020). Particularly, Quarton and Samsatli (2020) show that transportation of pure H_2 can significantly reduce linepack, with reductions ranging between 17% and 26% of the NG linepack. Notably, the extent of this reduction is contingent upon the operating pressure of the pipeline, with higher operating pressures yielding greater linepack reductions (Quarton and Samsatli, 2020). Uilhoorn (2009) presents a transient non-isothermal model to simulate a gas pipeline with blends of H_2 and NG. Specifically, the simulations were carried out maintaining the same flow rate demand or energy demand for three different H_2 concentrations. The results confirm the linepack reduction in the case of H_2 blends suggesting that the loss in linepack energy might cause problems in managing the supply and demand flow variations (Uilhoorn, 2009). Moreover, Zhang et al. (2022) investigate the effects of localized H_2 injections on linepack showing the error generated by adopting a fixed compressibility factor (Zhang et al., 2022). Mhanna et al. (2022) and Wang et al. (2023) demonstrate in their respective studies that linepack decreases in the presence of H_2 due to the reduction in HHV (Mhanna et al., 2022; Wang et al., 2023). Li et al. (2023) and Wu et al. (2024) instead focus on the coordination of electrical and gas networks seeing the linepack as a means of flexibility for managing the RES surplus but without focusing on the effects on the flexibility of the gas network itself (Li et al., 2023; Wu et al., 2024).

Previous studies have indicated that transporting a blend of NG and H_2 in a pipeline reduces the linepack. However, to the best of the authors' knowledge, no study has been conducted to investigate the viability of maintaining the linepack level in a pipeline transporting blends of natural gas and hydrogen, equivalent to the level observed when transporting natural gas alone. To fill this gap, this study specifically examines the offsetting or partial compensation of the linepack reduction caused by H_2 by adjusting the operating pressure or expanding the network. To achieve this goal, an optimization algorithm embedding a transient fluid-dynamic gas network model is introduced. The model is applied to two case studies, each involving a 250 km pipeline—one with a single pipeline layout, and the other with a looped pipeline of the same length. The range of hydrogen molar concentration in the blends considered spans from 0% to 100% H_2, intending to offer insights applicable to both low-blending future scenarios and scenarios where a complete transition of the pipeline from natural gas to hydrogen must be examined.

2 METHOD

This section introduces the non-linear programming (NLP) gas model used to optimize the pipeline operation. The first subsection presents the fluid-dynamic model, which serves as the cornerstone of the analysis. The second subsection describes the optimization function and the desired operating strategy of the pipeline.

2.1 Gas Network Model

This work adopts a transient, one-dimensional, isothermal gas network model. The governing equations necessary to describe a gas flow in a pipeline include the continuity equation and momentum equation. Under the common hypothesis of creeping motion and horizontal pipeline (Mhanna et al., 2022; Pambour et al., 2016; Zhang et al., 2022) the continuity and momentum partial differential equations

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(PDEs) are represented by Equations 1-2. These equations describe the temporal and spatial evolution of pressure p (Pa), density ρ (kg/m³), and $\dot{m}$ mass flow rate (kg/s) within a pipeline having a diameter D (m) and cross-sectional area A (m²).

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial \dot{m}}{\partial \mathrm{x}} = 0 \tag{1}$$

$$\frac{\partial p}{\partial x} + \frac{1}{A}\frac{\partial \dot{m}}{\partial t} + \frac{8 f \dot{m}^2}{\rho \pi^2 D^5} = 0 \tag{2}$$

Considering a pipeline l connecting two nodes i and j, and given a spatial discretization length Δx_l and a temporal discretization Δt, the aforementioned PDEs are numerically solved by an implicit one-dimensional first-order forward in time and second-order centered in space finite-difference scheme (Equations 3-4).

$$\frac{\left(\rho_{l,x+1}^{t} - \rho_{l,x+1}^{t-1} + \rho_{l,x}^{t} - \rho_{l,x}^{t-1}\right)}{2\Delta t} + \frac{\left(\dot{m}_{l,x+1}^{t} - \dot{m}_{l,x}^{t}\right)}{\Delta x_l A_l} = 0 \tag{3}$$

$$\frac{\left(p_{l,x+1}^{t} - p_{l,x}^{t}\right)}{2\Delta x_l} + \frac{\left(\dot{m}_{l,x+1}^{t} - \dot{m}_{l,x+1}^{t-1} + \dot{m}_{l,x}^{t} - \dot{m}_{l,x}^{t-1}\right)}{4A_l \Delta t} + \frac{2f_l\left(\dot{m}_{l,x}^{t} + \dot{m}_{l,x+1}^{t}\right)^2}{\pi^2 D_l^5 \left(\rho_{l,x+1}^{t} + \rho_{l,x}^{t}\right)} = 0 \tag{4}$$

Where x and $x+1$ represent two adjacent nodes belonging to the set of fictitious nodes obtained by the spatial discretization. Under the hypothesis of steady-steady condition, the momentum equation is represented by Equation 5:

$$p_i^2 - p_j^2 = \frac{16}{\pi^2 R_{air}} \cdot \frac{f_l SG L_l Z_l T}{D_l^5}\left(\frac{p_{std}}{T_{std}}\right)^2 \cdot \left(\frac{\dot{m}_l}{\rho_{std}}\right)^2 \tag{5}$$

Being pipelines typically characterized by high flow rates is reasonable to approximate the Darcy friction factor f, through the NPK formula for fully turbulent flows, shown in Equation 6.

$$\frac{1}{\sqrt{f_l}} = -2\log_{10}\left(\frac{\varepsilon_l}{3.7 \cdot D_l}\right) \tag{6}$$

Nodes are the elements of gas networks that topologically can act as connections, supply points or demand points. To close the set of equations necessary to describe a gas network problem, two equations are evaluated in the nodes: the real gas law (Equation 7) and the nodal mass balance (Equation 8). Considering a node i:

$$p_i = \rho_i Z_i R_g T_i \tag{7}$$

Where Z is evaluated through the SRK cubic relation (Soave, 1972). The nodal mass balance is described by Equation (8):

$$\dot{m}_{s,i}^{t} + \left(\sum_{\mathrm{j}=1}^{n} \dot{m}_{ji}^{t} - \sum_{j=1}^{m} \dot{m}_{ij}^{t}\right) = \dot{m}_{dmd,i}^{t} \tag{8}$$

where the subscript s indicates the supply point, $\sum_{\mathrm{j}=1}^{n} \dot{m}_{ji}^{t}$ and $\sum_{\mathrm{j}=1}^{n} \dot{m}_{ij}^{t}$ represent respectively the sum of the flow rate incoming and outgoing through a pipeline in the node i and $\dot{m}_{dmd,i}^{t}$ represents the mass

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flow rate demand at node *i,* calculated from the energy demand by dividing it by the HHV of the mixture. The calculation of the HHV of a mixture of gases is presented in detail in (Guzzo et al., 2024).

2.2 Optimization Function and Operating Strategy

The paper primarily focuses on analyzing the effects of H_2 on linepack. Linepack represents the amount of energy stored in a pipeline *l*. Taking a snapshot of the pipeline at a certain time *t*, and avoiding the subscript *l* for readability, linepack Lp^t [MJ] can be expressed by Equation 9 as:

$$Lp^t = \frac{p_{avg}^t}{p_{std} Z_{avg}^t} A \, L \, HHV \tag{9}$$

where $p_{avg}^t = \frac{2}{3}\left(p_i^t + p_j^t - \frac{p_i^t p_j^t}{p_i^t + p_j^t}\right)$ and $Z_{avg}^t = 0.5\left(Z_i^t + Z_j^t\right)$ are respectively the average pressure and compressibility factor in the pipeline. Additionally, the temporal evolution of linepack within a pipeline can be characterized by updating the value at time $t-1$, with the sum of the inflows and outflows at time *t* (Equation 10).

$$Lp^t = Lp^{t-1} + (\dot{m}^t{}_{ij,in} - \dot{m}^t{}_{ij,out}) \frac{HHV}{\rho_{std}} \; \Delta t \tag{10}$$

The test cases outlined in the following section share a common optimization objective. The goal is to compare scenarios characterized by different mixtures of natural gas and hydrogen, maintaining the same level of target linepack within the system at the beginning and end of each day. This objective is achieved by minimizing the difference between the linepack at the initial timestep and a predefined target linepack (Equation 11), alongside implementing a supply strategy that regulates the flow supplied. The supply strategy, as depicted in Equation 12, dictates that the aggregate gas flow rate supplied at the supply points must equal the time-integrated average demand across all nodes.

$$min \;\; f_{obj} = \; Lp^{t=0} - Lp_{target} \tag{11}$$

$$\sum_i \dot{m}_{s,i}^t = \frac{1}{24 \cdot 3600} \int_0^{8760} \sum_i \dot{m}_{dmd,i}^t \, dt \tag{12}$$

The optimization problem is implemented in Pyomo environment and solved using IPOPT.

3 CASE STUDY

Figure 1 shows the two layouts considered in the test cases. Figure 1a represents a pipeline that connects a supply node and a demand node. The length of the pipeline is $L = 250$ km, and the diameter $D = 0.4$ m. Figure 1b shows the second layout considered which consists of the same pipeline of Figure 1a, looped with another pipeline of the same length and diameter $D = 0.52$ m. The roughness is assumed equal to $\varepsilon = 0.015$ mm in both layouts. The gas temperature and the ambient temperature are considered constant and equal to 15 °C. The maximum allowable operating pressure (MAOP) of the pipelines is 10.2 MPa, while the minimum delivery pressure (MDP) to the end user is 3.0 MPa. The NG considered has the following composition, expressed in molar fraction: CH_4 = 88.396, C_2H_6 = 6.554, C_3H_8 = 0.00, C_4H_{10} = 0.00, CO_2 = 1.86, N_2= 3.19, H_2 = 0.00. Figure 2 shows the demand profile requested by the user node, expressed in terms of energy per unit of time rather than mass. This method, commonly referred to in the literature as the 'energy demand' approach, enables the comparison of scenarios with varying gas compositions while meeting identical user requirements. The time interval analyzed is 24 hours. The average demand is equal to 3.75 TJ/h, peaks occur at 3:00 and 15:00, reaching 6.25 TJ/h, while the demand drops to 1.25 TJ/h at 9:00 and 21:00. The pipeline is operated maintaining a target value of the linepack at the beginning and end of the day. The target linepack is defined to be equal to 100.0 TJ, almost 26.67 times the average demand.

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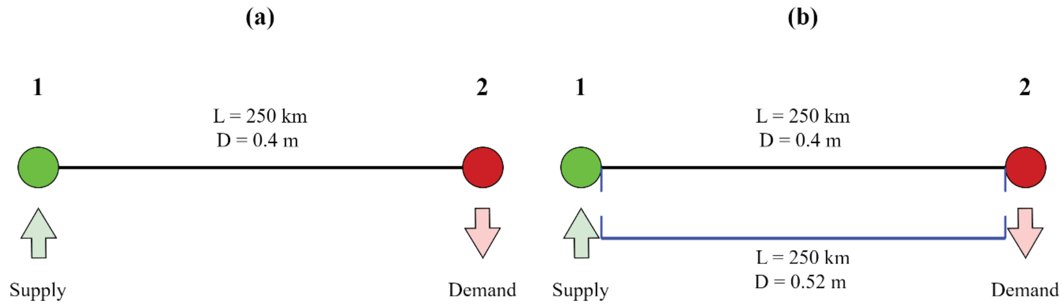

Figure 1: Test case layouts: (a) current layout of the pipeline system, (b) proposed system expansion involving a looped pipeline

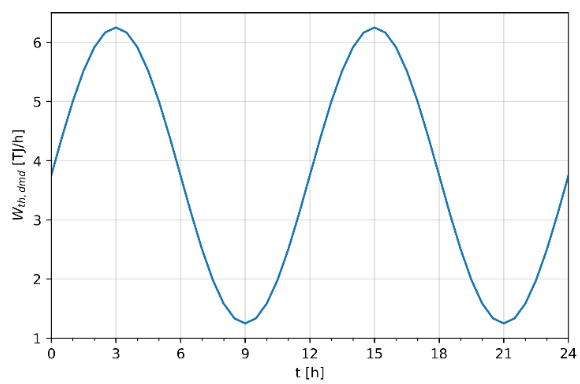

Figure 2: Thermal demand at node 2

The goal of the analysis is to explore the possibility of maintaining the same linepack level transporting different blends of NG and H_2. Table 1 reports the characteristics of the three different test cases analyzed. The optimization function is the same and consists of maintaining the same linepack level when transporting different blends of H_2 and NG. More specifically, defined a target linepack the optimization problem aims to minimize the difference between the target linepack and the actual linepack. Case 1 and Case 2 are characterized by the same layout shown in Figure 1a and differ by being constrained by MAOP and MDP (Case 1) or unconstrained (Case 2). Case 3 instead considers the layout in Figure 1b where the pipeline in Figure 1a is looped by another one and assumes the same pressure constraints of Case 1. The H_2 molar fraction in the mixtures considered spans from 0% to 100%.

	Case 1	**Case 2**	**Case 3**
Layout	Figure 1a	Figure 1a	Figuer 1b
Optimization Function	Equation 11	Equation 11	Equation 11
Target Linepack	100 TJ	100 TJ	100 TJ
Constraints	$MDP \leq p \leq MAOP$	Unconstrained	$MDP \leq p \leq MAOP$
H_2 [%mol]	0-100%	0-100%	0-100%

Table 1: Test cases characteristics

4 RESULTS AND DISCUSSION

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This section delves into the results, starting with the definition of a reference case mirroring the current pipeline operation. Subsequently, three distinct scenarios (Case 1, Case 2, and Case 3) are compared against this reference. Each scenario involves simulations across eleven H_2 concentrations ranging from 0%mol to 100%mol, with a consistent 10%mol increment.

Figures 4a-5a-6a, in the subsections regarding Case 1-Case 2-Case 3, illustrate the non-dimensional variation of key variables involved in linepack calculation at the initial timestep of the simulation. This provides insight into how the three scenarios diverge across all eleven compositions, ranging from 0% to 100% H_2 molar fraction. Figures 4b-5b-6b presented in subsections regarding Case 1-Case 2-Case 3 show the temporal evolution of the nodal pressures for the cases having (0-10-20-30-100) %mol of H_2. This decision is motivated by two factors. Firstly, from a technical standpoint, future scenarios typically encompass the use of H_2 blends with low concentrations, avoiding high molar fractions, before transitioning directly to dedicated pipelines for transporting pure H_2. Secondly, this choice enhances plot visibility by focusing on fewer blends, while still capturing all significant outcomes.

4.1 Reference Case

The reference case is based on the pipeline configuration depicted in layout A, which represents the current operation of the pipeline when transporting NG. This configuration serves as a representation of the pipeline's present operational state. Figure 3a shows the supply strategy, described in Equation 12, and adopted to maintain the same linepack level at the beginning and the end of the day (Equation 11). The supply maintains a constant energy supply equivalent to the average demand. When demand exceeds supply, the linepack decreases, and vice versa, resulting in linepack swings between 90.5 TJ and 100.0 TJ throughout the day. Figure 3b shows the fluid-dynamic implications of operating the pipeline with a target linepack equal to 26.67 times the average energy demand. Figure 3b reveals a significant safety margin in pressures considering both the MAOP at the inlet node and the MDP at the outlet node. The inlet pressure swings between 7.50 MPa and 7.90 MPa, the pressure at the outlet node swings as a function of the demand between 5.30 MPa and 6.90 MPa and the average pressure of the pipeline, calculated as explained in the model, swings between 6.70 MPa and 7.30 MPa. Figure 3b also shows that due to the dynamic nature of the pipeline, the pressure swing becomes more pronounced as we approach the demand point. Additionally, the delay between the peak demand and the minimum pressure increases as we move upstream.

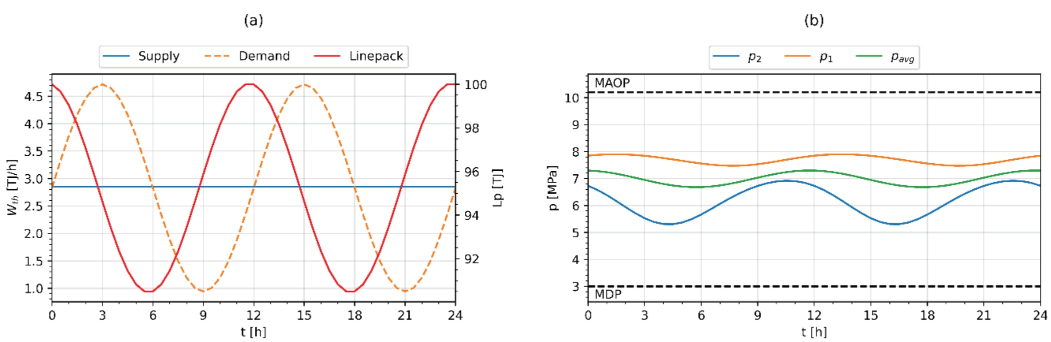

Figure 3: Reference case (Case 1 with NG): a) supply strategy, b) inlet-outlet-average pressure swings in the pipeline.

4.2 Case 1: H_2 Blending in the Actual Pipeline System

As previously mentioned, Case 1 considers the actual layout of the pipeline (Figure 1a), operating within the real pressure constraints, (upper limit = MAOP, lower limit = MDP). Increasing the H_2 content in the blend, the HHV decreases, and the compressibility factor Z increases. This combination of factors results in a reduction in the linepack of the pipeline. To maintain the same linepack level, the sole option is to elevate the average pressure within the pipeline. This can be achieved by increasing the inlet pressure of the pipeline. Figure 4a illustrates that compensating for the linepack reduction associated

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with HHV and Z up to a blend of 20% mol H_2 is feasible by increasing the inlet pressure p_1 (and therefore p_{avg}). Figure 4b explains the reduction in linepack seen in Figure 4a. In particular, it illustrates that once the H_2 molar fraction reaches 30%, the inlet pressure p_1 value hits the MAOP constraint, restricting additional increases in p_{avg} necessary to offset the linepack reduction. After reaching 30% mol of H_2, the rate of linepack reduction accelerates and then decelerates as the average pressure initially decreases and then increases. This behavior is attributed to the nonlinear rise in pressure losses and the slope of the Z factor with increasing H_2 content. This scenario demonstrates that the pipeline can operate within the pressure limits for all H_2 molar fractions while maintaining a safety margin on the delivery pressure. Moreover, it's feasible to preserve the same linepack by adjusting the inlet pressure for low H_2 contents. However, for pure H_2, the linepack is 65% less than target linepack shown in the reference case.

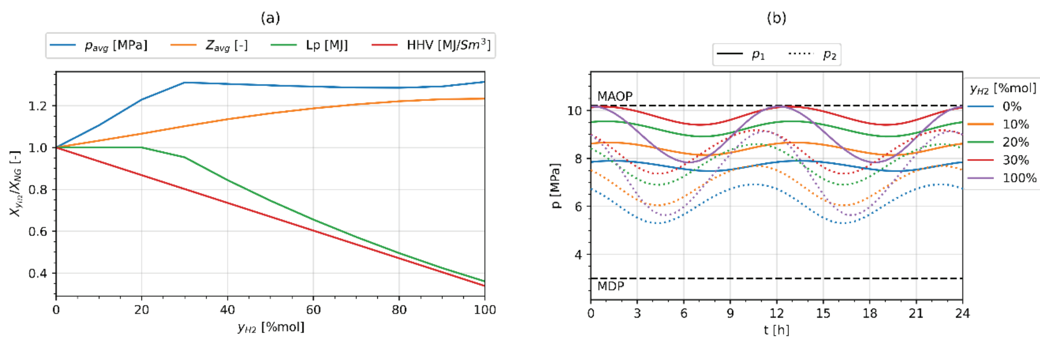

Figure 4: Case 1 results: a) Variation of relevant variables across a range of H2 %mol from 0 to 100% at t = 0, normalized against the reference case; b) Evolution of pipeline inlet and outlet pressures over time for H2 concentrations of 0%, 10%, 20%, 30%, and 100%

4.3 Case 2: H_2 Blending in the Actual Pipeline System Unconstrained

Case 2 serves as a theoretical exercise aimed at illustrating the necessary pressure increase required to maintain consistent linepack levels across all H_2 concentrations, ranging from 0% to 100%, within the gas transported through the pipeline presented in Figure 1a. To achieve this objective, the pressure constraints on the pipeline are eliminated. Consequently, Figure 5a shows that the linepack remains constant, thanks to the average pressure within the pipeline that is allowed to increase freely, offsetting the reduction of the HHV and the rise of Z. The pseudo-hyperbolic rise in average pressure underscores the necessity of operating the pipeline at an average pressure exceeding four times that of the reference case. Figure 5b illustrates, consistently with the findings presented in the previous section, that a blend containing 30% H_2 or higher, necessitates an inlet pressure exceeding the MAOP. Specifically, for pure H_2, the pipeline would require an inlet pressure reaching up to 30.0 MPa. The impracticality of this approach stems from material limitations. Operating pipelines at such high pressures would subject them to excessive stress, leading to fractures and structural failure.

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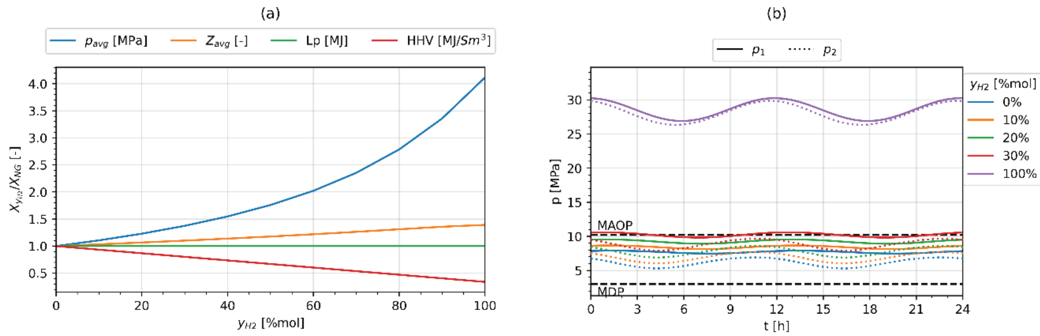

Figure 5: Case 2 results: a) Variation of relevant variables across a range of H2 %mol from 0 to 100% at t = 0, normalized against the reference case; b) Evolution of pipeline inlet and outlet pressures over time for H2 concentrations of 0%, 10%, 20%, 30%, and 100%.

4.4 Case 3: H_2 Blending after Expanding the Actual Pipeline System

Case 3, on the other hand, presents a technical solution to address the reduction in linepack. In this scenario, the pipeline layout is modified (Figure 1b), with the proposal to loop the pipeline by installing a parallel line. This approach offsets linepack decrease due to H_2 by increasing the geometric volume of the pipeline. Specifically, the length and diameter of the pipeline are chosen to offset the linepack reduction observed in the scenario with 100% H_2. In this case, it is noteworthy to observe that the pipeline can maintain the target linepack of the reference case for all blends except the scenario involving pure NG. Indeed, Figure 6a illustrates that with pure H_2, an increase in the operating pressure is still necessary to compensate for the linepack reduction, even with an increased volume compared to the reference case. However, when reducing the H_2 content below 80% mol, the pipeline operates under the average pressure of the reference case. This is due to a combined effect, primarily resulting from the reduction of p_1 and secondarily from the decrease in pressure losses resulting from the split of the flow rates between the two looped pipelines. Figure 6b clarifies why the linepack exceeds the target for the NG case. Operating the looped pipeline with pure NG and a target linepack equal to the reference case, the pressure reduction at p_1 leads p_2 to reach the constraint on the MDP. Hence, as long as a reduction in pressure below the MDP, necessary to maintain the same level of linepack, is not acceptable, the results show a linepack increase.

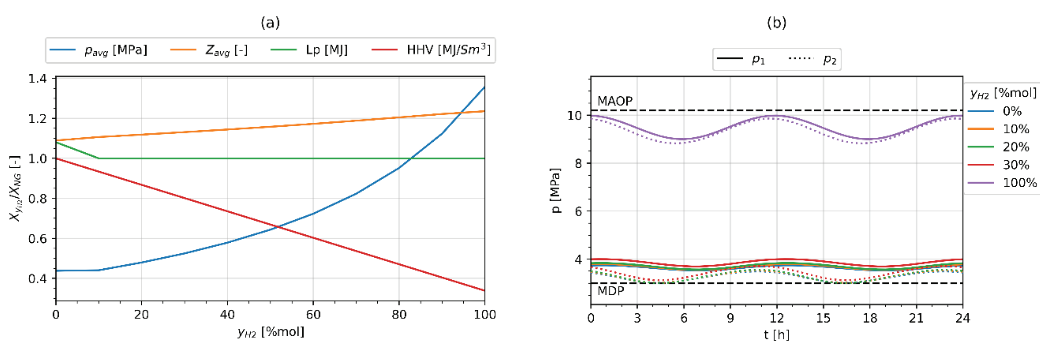

Figure 6: Case 3 results: a) Variation of relevant variables across a range of H2 %mol from 0 to 100% at t = 0, normalized against the reference case; b) Evolution of pipeline inlet and outlet pressures over time for H2 concentrations of 0%, 10%, 20%, 30%, and 100%.

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5 CONCLUSIONS

NG pipelines play a pivotal role in the current energy landscape. These pipelines form the backbone of energy infrastructure, facilitating the delivery of NG from production sites to end consumers across vast distances. Nevertheless, in the context of the urgent need to decarbonize the energy sector, there is a growing acknowledgement of the necessity to convert these pipelines to accommodate cleaner energy vectors such as H_2. Blending NG with H_2 represents an initial step towards decarbonization. However, to achieve a more significant reduction in carbon emissions, a shift towards dedicated pipelines for transporting pure H_2 will be necessary in the future.

This study examines the impact of H_2 blending on linepack, which represents the energy content stored in the pipeline and, as such, serves as an indicator of the flexibility of the system. Blending H_2 in NG affects the thermochemical properties of the gas mixture, resulting in a reduction of the HHV, and consequently in a linepack reduction. This paper investigates two strategies a pipeline operator may employ to offset the linepack decrease caused by H_2: i) increasing the operating pressure of the pipeline; ii) expanding the network by installing a looping pipeline. Increasing the operating pressure has proven effective in maintaining the desired linepack, for blends containing up to 20% H_2. However, the transportation of pure hydrogen in the existing pipeline, while maintaining the same linepack level, would necessitate an operating pressure approximately four times higher than the actual pressure level. Such operating pressures are not acceptable as they result in exceeding the material stress tolerance limits. Hence, considering the technological limitation, Case 3 demonstrates that maintaining the desired linepack is feasible by installing a looped pipeline. Both strategies will inevitably increase the gas transportation costs. Indeed, an increase in the operating pressure will increase the compression ratio at the compressor stations, which will in turn increase the variable costs associated with the power required at the prime mover. Conversely, the installation of a looped pipeline will require investment, which will increase the capital costs of the system.

Future research efforts may be directed towards incorporating compressors into the model to evaluate the economic viability of potential strategies to offset reductions in linepack resulting from the transportation of hydrogen. Additionally, these investigations could be extended to larger network systems, thereby examining the algorithm robustness on a broader scale.

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NOMENCLATURE

A	Pipe area	(m^2)
D	Pipe diameter	(m)
ε	Roughness	(m)
f	Friction factor	(–)
f_{obj}	Friction factor	(MJ)
HHV	Higher Heating Value	(MJ/Sm^3)
L	Pipe length	(m)
Lp	Linepack	(MJ)
$\dot{m}$	Mass flow rate	(kg/s)
MAOP	Maximum Allowable Operating Pressure	
MDP	Minimum Delivery Pressure	
NLP	Nonlinear Programming	
NG	Natural Gas	
W	Power	(MW)
p	Pressure	(Pa)
PDE	Partial Differential Equation	
R_g	Gas constant	(J /(kg K))
RES	Renewable Energy Source	
T	Temperature	(K)
Z	Compressibility factor	(–)
ρ	Density	(kg/m^3)
Δt	Time discretization length	(s)
Δx	Space discretization length	(m)
y_{H2}	hydrogen molar fraction	(–)

Subscripts and superscripts

avg	average
dmd	demand
el	electricity
g	gas
i,j	nodes indexes
ij	pipeline indexes
in	pipeline inlet
l	pipeline
out	pipeline outlet
std	standard
t	Index for time discretization
th	thermal
x	Index for spatial discretization

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