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Enhancing and optimization of green hydrogen mixtures in natural gas to optimize transportation, power, and Economy

Hassan M. M. Mustafa [1]*, Rozan M. Kamal[2], R. M. Mohamed[2]
[1] *Mechanical Engineering Department, Engineering and Renewable Energy Research Institute, National Research Centre, Giza, Egypt.*
[2] *Chemical Engineering Department, Canal High Institute of Engineering and Technology, Suez, Egypt.*

Abstract
The issue of fulfilling the growing worldwide energy demand while minimizing environmental consequences through the exploration of hydrogen fuel's potential as a sustainable energy solution. Hydrogen, produced through electrolysis, offers a promising way to decrease carbon emissions without contributing to climate change. The research considers the complexities of hydrogen transportation, recognizing the need for specialized infrastructure due to hydrogen's high diffusivity. The primary emphasis of the study revolves around incorporating hydrogen into the existing natural gas pipeline system as a financially viable option. The research utilizes tools like the General Algebraic Modelling System (GAMS) and design expert tools to identify the most suitable blend ratios of hydrogen and natural gas for secure and effective transportation. The analysis also evaluates the economic implications of different blend proportions, including the costs associated with modifying the infrastructure. Through computational analysis, the study quantifies the energy and cost requirements for compressing and transporting the gas blends, considering variables such as pipeline diameter, hydrogen injection ratio, and flow rate. The findings reveal that an optimal mix, comprising a 20% hydrogen injection rate, a flow rate of 616.459 million standard cubic feet per day, and a 36-inch pipeline diameter, results in the lowest energy use of 13831.097 HP and transportation cost of 314.673 million $/yr., with a desirability of 87.1%. This optimal configuration promotes a balanced approach to energy security, accessibility, and sustainability.

Keywords: Alternative fuels, Economic challenges, Hydrogen injection ratio, Pipeline transmission optimization.

Introduction

In recent times, the global community has faced an energy crisis stemming from resource depletion and heightened environmental concerns [1][2]. The extensive utilization of fossil fuels in our present energy framework stands as the primary contributor to human-caused carbon dioxide emissions, significantly linked to global warming and shifts in climate patterns. Alongside diminishing reserves of crude oil and geopolitical unrest in major oil-rich areas, stringent emission standards are fostering a demand for substitute fuel sources [3] [4]. An alternate fuel must possess technical viability, economic competitiveness, environmental suitability, and widespread accessibility. Numerous alternative fuel options have been proposed, including biodiesel, methanol, ethanol, hydrogen, boron, natural gas, liquefied petroleum gas (LPG), Fischer–Tropsch fuel series, electricity, and fuels derived from solar energy [5]. Among these substitute fuels, hydrogen possesses the greatest specific energy content among traditional fuels and stands as the most prevalent element in the cosmos. Hydrogen stands ready to make a substantial contribution to sustainable advancements, given its capacity to be produced in abundant quantities using renewable energy sources (RES) in the predictable future. The future market viability of hydrogen hinges primarily on four factors: (1) the prospective cost of hydrogen, (2) the pace of advancements in hydrogen-utilizing technologies, (3) potential enduring limitations on greenhouse gases, and (4) the expenses associated with competing energy systems [4].

Hydrogen presents itself as a futuristic ideal fuel, boasting numerous social, economic, and environmental advantages. It holds the enduring potential to diminish reliance on foreign oil and decrease both carbon and criterion emissions from the transport industry. It's been only in the recent decade that the concept of a hydrogen-based economy post fossil fuel era has begun to capture widespread attention. Hydrogen's remarkable energy yield of 122 kJ/g (kilojoules per gram) stands at 2.75 times higher than that of hydrocarbon fuels [6][7].

* Corresponding author: HassanAbuHashish@gmail.com , (Hassan M. M. Mustafa).
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Currently, research is being conducted to utilize hydrogen in both conventional combustion engines and fuel-cell electric vehicles. The worldwide hydrogen market already exceeds $40 billion annually [8], encompassing its utilization in ammonia production (49%), petroleum refining (37%), methanol production (8%), and various other minor applications (6%) [9]. The annual sales of hydrogen have demonstrated a 6% rise over the past five years, closely linked to its expanded application in refineries due to more rigorous fuel quality standards. The current usage of hydrogen equates to 3% of overall energy consumption, with an anticipated growth rate ranging between 5% and 10% annually [10]. In the pursuit of green hydrogen production, electrolyzers are used utilizing renewable energy sources. The production process called electrolysis, where an electric current is passed through water (H2O) to separate it into hydrogen and oxygen[11] [12]. When this electricity is sourced from renewable energy, such as solar or wind power, the process is considered "green" as it generates hydrogen without associated carbon emissions, making it a sustainable energy source. Electrolyzers typically use proton exchange membrane (PEM) or alkaline electrolysis technologies to facilitate this separation [13]. The hydrogen produced can be utilized in various sectors, including transportation, industry, and power generation [14]. Green hydrogen is gaining traction as a clean energy carrier, offering potential for decarbonizing sectors that are challenging to electrify directly [15]. Its adaptability and potential for large-scale energy storage make it an attractive option for achieving climate and energy goals. The advancement of electrolyzer technology, the decreasing costs of renewable energy, and the growing emphasis on decarbonization have contributed to the increasing interest in green hydrogen production using electrolyzers [16].

Transporting hydrogen presents economic challenges related to its appropriate distribution. Trucks and ships are suitable for transporting hydrogen using pressurized containers, whether in its compressed gas form (GH2) or as a liquid (LH2) [17]. Compressed gas necessitates relatively high pressures (180 bar or higher) and demands the construction of three to four times more infrastructure [18]. While liquid hydrogen effectively enhances the density by a factor of 800 [9], it mandates an energy-intensive liquefaction process and specialized cryogenic insulated tanks to maintain requisite low temperatures [19]. As an alternative, compressed liquid ammonia can be employed to transport large quantities of hydrogen to distant areas using trucks or ships [20]. The cost-effective provision of energy for hydrogen conversion depends on the availability of local resources and the selected mode of transportation. Pipelines are considered the most economical method for transporting significant volumes of hydrogen, with cost projections ranging from $0.05 to $3 per ton depending on distance. While trucks and ships are viable alternatives for hydrogen transportation, the low density of hydrogen requires pressurization into a compressed gas (around 18 MPa) or liquefaction to achieve high-density energy, leading to increased costs associated with infrastructure and processes for compression and liquefaction [21].

Hydrogen delivery plays a pivotal role in establishing a sustainable hydrogen economy, necessitating an infrastructure to convey hydrogen from its production site to the dispensing point at a refueling station or stationary power facility. Two main types of hydrogen delivery are under deliberation [22]: (1) The transmission of hydrogen, moving from a central hydrogen production facility to a specific destination, and (2) the distribution of hydrogen, extending from a central hydrogen plant to a distributed network of refueling stations within a city or region.

A blend of these three alternatives may be employed across different phases of hydrogen fuel market advancement [23]:

- Tube trailers could be deployed during the initial introductory phase due to the likely modest demand, thus circumventing the boil-off associated with storing liquid hydrogen.
- Cryogenic tanker trucks could transport larger quantities than tube trailers to satisfy the requirements of expanding markets.
- Pipelines could be strategically positioned to convey hydrogen to high-demand areas as additional production capacities come online.

While pipelines represent a cost-effective long-term solution, their implementation faces challenges due to the need for specialized infrastructure like hydrogen pipelines and compressors, creating economic barriers. A promising strategy to address this obstacle entails mixing hydrogen with natural gas in current pipeline networks. Nevertheless, the distinctive characteristics of the combined gas may present operational, material, and safety concerns, requiring adjustments to the existing system [24].

Various studies have explored hydrogen transportation in pipelines, including projects like the Fort Saskatchewan Hydrogen Blending project with a 5% H_2 concentration [25], and H_2 projects with 100% hydrogen concentration [17].

This research paper seeks to delve into the feasibility of producing hydrogen through electrolyzers and subsequently integrating this hydrogen, combined with a renewable energy source, into established natural gas pipelines as a cost-effective method for transporting substantial quantities of hydrogen [26]. The study's core focus lies in optimizing the mixture of hydrogen and natural gas within pipeline networks, employing modeling tools like the General Algebraic Modeling System (GAMS) and design expert. The primary goals encompass pinpointing the ideal blend ratios of hydrogen within the natural gas pipeline, assessing the associated costs, and determining the optimal parameters for variables like injection ratio, line diameter, and mixture flow rate.

Materials and Methods

Materials

Hydrogen production from electrolyzer.

Green hydrogen is produced through the process of water electrolysis, utilizing sustainable energy sources such as solar, wind, or hydroelectric power Figure 1. In contrast to conventional hydrogen production methods dependent on fossil fuels and emitting greenhouse gases, green hydrogen is emission-free when used, signifying its potential as a clean future fuel [27]. Hydrogen production through electrolysis involves two main types: alkaline electrolysis and proton exchange membrane (PEM) electrolysis [28]. Alkaline electrolyzers use an alkaline electrolyte solution, typically potassium hydroxide, and have been widely used for several decades. On the other hand, PEM electrolyzers use a solid polymer electrolyte, offering advantages such as higher efficiency, rapid response to changes in electrical input, and the ability to operate at higher pressures. When considering the environmental impact, the process is emissions-free if powered by renewable energy sources, making it a key element in the quest for sustainable energy [13]. Moreover, the produced hydrogen can be stored and used as a clean energy carrier for fuel cell vehicles, industrial processes, and energy storage, contributing to decarbonization efforts.

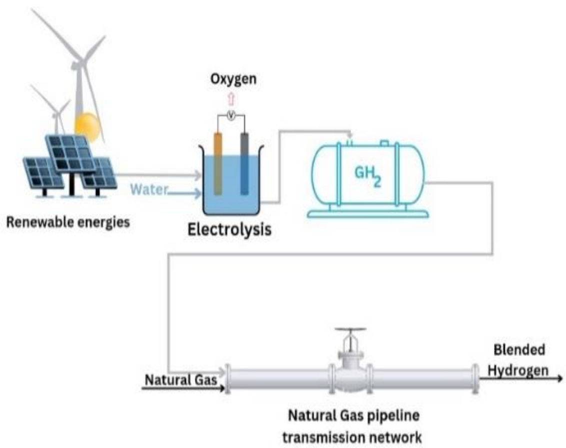


Figure 1 Hydrogen production from electrolyser

The primary production method involves electrolysis, where an electrolyzer powered by renewable electricity is used to split water into hydrogen and oxygen, with electrolysis being the predominant approach [29]. Additionally, photoelectrochemical (PEC) cells utilize sunlight to directly split water into hydrogen and oxygen, integrating power generation and electrolysis. While less common and efficient, biological processes involving microorganisms can ferment biomass to produce hydrogen [30].

Natural gas

Natural gas, an adaptable and plentiful hydrocarbon fuel, represents a fundamental element within the global energy array. Predominantly constituted of methane, it functions as a clean-burning substitute across diverse applications, encompassing electricity generation, heating, and industrial procedures [31]. Its comparably lower carbon intensity in relation to other fossil fuels renders it an appealing choice for mitigating greenhouse gas emissions [32]. Extraction of natural gas from subterranean reservoirs occurs through drilling and well operations, while its efficient conveyance via pipelines or in the form of liquefied natural gas (LNG) ensures a dependable provision to end users. Through its contribution to bolstering economic expansion, fortifying energy resilience, and aiding the shift towards more sustainable energy, natural gas remains an indispensable factor in addressing the global energy requisites [33].

Blending and transportation of Hydrogen with Natural gas

Blending hydrogen with natural gas within current pipeline systems provides a cost-effective means to transmit large quantities of hydrogen across extensive distances without requiring new infrastructure [34]. Nonetheless, due to hydrogen's smaller size and distinct physical properties, including lower volumetric density and viscosity, its interaction with natural gas may create unique behaviors. These behaviors could potentially pose safety hazards for pipelines initially designed for natural gas transport. To ensure energy equilibrium, the combined gas mixture might require transportation at elevated flow rates, contingent upon hydrogen concentration. This could lead to heightened operational pressures, potentially surpassing the intended capacities of compressors and pipelines, originally engineered for natural gas conveyance [20]. Hence, it is imperative to contemplate design alterations to guarantee the secure conveyance of blended hydrogen through existing pipeline systems, while identifying any associated risks and operational challenges stemming from hydrogen concentration. Achieving a uniform, homogeneous state of the blended gas throughout the pipeline is critical. If the two gases exhibit notably different densities, stratification may occur, resulting in varying flow behaviors and leak tendencies [35]. This non-uniform distribution could lead to uneven energy dispersion and operational complications within the pipeline. Table 1 provides a summary of the physical properties and energy content of each gas at a temperature of 20°C and a pressure of 101.35 kPa.

Transporting hydrogen with natural gas involves using existing natural gas pipelines, which requires assessing the compatibility of materials and ensuring safety [36]. While hydrogen has a lower energy density compared to natural gas, it can be transported through pipelines with appropriate adjustments. However, dedicated hydrogen pipelines are also being considered due to the unique properties of hydrogen, which may offer more efficient transportation in the long term [37].

Table 1 Physical properties and energy content of Hydrogen and Methane [38].

	Hydrogen (H_2)	Methane (CH_4)	Unit
Molecular weight	2.02	16.04	g/mol
Critical temperature	33.2	190.65	K
Critical pressure	13.15	45.4	bar
Vapor density at 293 K and 1 bar	0.0838	0.651	Kg/m3
Specific heat ratio (C_p/C_v)	1.4	1.31	
Lower heating value	120	48	MJ/Kg
Higher heating value	142	53	MJ/Kg
Maximum flame temperature	1800	1495	K
Autoignition temperature in air	844	813	K

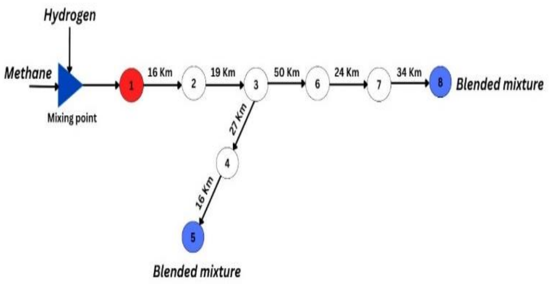


Figure 2 Simplified natural gas pipeline transmission network.

Methods

The research utilizes a simplified natural gas pipeline transmission network Figure 2 with 8 nodes, including one source node and two demand nodes. The pipeline operates at a temperature of 298 K. The primary flow in the natural gas pipeline is methane, while the objective for hydrogen is to achieve an average concentration ranging from 5% to 20%. Within this network, there is a branch carrying pure hydrogen alongside co-flowing natural gas.

The evaluation involved analyzing the change in the gas volume transported after blending methane and hydrogen, increasing from 200 to 600 MMSCFD.

This investigation also considered the varying pipeline diameter, which expanded from 28 to 36 inches. Each segment of the network has different lengths, and the pressure ranges from 1379 to 5515.81 kilopascals.

Various methodologies will be employed to attain the most optimal solution for blended natural gas transmission pipeline. These approaches encompass diverse mathematical models designed to minimize energy consumption and thereby lower overall expenses. These models are aimed at optimizing the transportation process for blended gas, ensuring cost-effective and sustainable operations.

Computational formulas

Gas compressibility factor

The compressibility factor (Z) is calculated using an equation of state Equation (1), allowing the determination of Z based on the critical properties of the gas mixture, the average pressure of the pipe segment, and a constant assumed temperature [39].

$$Z = 1 + 0.257\left(\frac{P_{avg}}{P_c}\right) - 0.533\left(\frac{P_{avg}}{P_c}\right)\left(\frac{T_c}{T_{avg}}\right) \quad (1)$$

Power consumption

In a blended natural gas pipeline transmission system, the focus is on minimizing total power consumption and fuel usage. This involves optimizing the operation of the system to reduce overall energy consumption using equations (2) while efficiently transporting the blended natural gas through the pipeline network. Strategies may include adjusting compression levels, managing flow rates, and considering the specific properties of the gas mixture to minimize power requirements and fuel consumption [40]. The goal is to find an operational balance that maximizes energy efficiency and minimizes the overall environmental impact of the transmission system.

$$P = ZRT * \frac{Q}{Mw\ gas} * \left(\frac{k}{k-1}\right) * \left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right) \quad (2)$$

Total cost minimization

The total cost will perform as the optimization process's objective function using equations (3-6) [41].

Total cost= (Investment cost+ operating cost) $_{pipe}$+ (Investment cost+ operating cost) $_{compressor}$

Pipe calculations

Pipe investment cost

$$CIP = (1 + R_p)C_p L^l d^m \frac{(1+r)^n r}{(1+r)^n - 1} \quad (3)$$

Pipe operating cost

$$OC_{pipe} = C_{fp} \frac{(1+r)^n r (1+R_p) C_p L^l d^m}{(1+r)^n - 1} \quad (4)$$

Compressor calculations

Compressor investment cost

$$CIC = C_{hp} HP^b \frac{(1+r)^n r}{(1+r)^n - 1} \quad (5)$$

Compressor operating cost

$$O\ C_{comp} = XE_{LC} \quad (6)$$

Modeling and calculation technique

The General Algebraic Modeling System (GAMS) serves as a crucial asset in optimizing the power efficiency and cost-effectiveness of natural gas pipeline transmission networks [42]. When applied to this domain, GAMS not only aids in formulating and solving intricate optimization problems related to power consumption and cost efficiency but also empowers the development of comprehensive mathematical models that address diverse objectives [43]. These objectives encompass the minimization of power consumption, reduction of operational costs, and maximization of overall network efficiency by considering factors such as pipeline routing, compressor station locations, pipeline diameters, and pressure levels to achieve the most energy-efficient and cost-effective configuration [44].

By exploiting GAMS, engineers and analysts can construct models that integrate constraints tied to power usage, operational costs, and network performance, subsequently fine-tuning them to pinpoint the most efficient and cost-effective strategies for transporting natural gas through the pipeline network [45]. Additionally, GAMS facilitates scenario analysis, enabling the exploration of various operational and investment strategies aimed at optimizing power consumption and cost-effectiveness within natural gas transmission networks. This involves evaluating the impact of infrastructure upgrades, shifts in demand patterns, or the integration of renewable energy sources to [43] enhance the overall efficiency and sustainability of the network.

Eventually, the application of GAMS in optimizing the power and cost considerations of natural gas pipeline transmission networks provides decision-makers with a potent instrument for enhancing energy efficiency, cost-effectiveness, and overall performance, all while aligning with environmental and economic goals [45].

Optimization techniques using software.

Design Expert is a statistical software method developed by StateEase. Initially launched in 1996, its primary purpose is to facilitate experimental designs, including the determination of optimal formulations. In addition to its optimization capabilities, the software can also interpret the experiment's factors. It is segmented into three research directions, catering to the specific experimental design: screening, characterization, and optimization [46]. The software was employed to conduct a comprehensive analysis of the cost factors involved in transporting varying quantities of hydrogen through natural gas pipelines. Additionally, it facilitated an examination of the energy consumption patterns of the compressors essential for the transportation of diverse hydrogen volumes within the natural gas transmission network. This allowed for a detailed understanding of the economic and energy-related aspects associated with integrating hydrogen into natural gas transmission systems. Through an analysis of these factors, the software aids in ascertaining the optimal injection and flow rate ratio as well as the most suitable diameter for the transmission lines with minimum transportation costs and reduced energy consumption in the associated compressors. Table 2 showed 17 experimental runs. They were suggested by a Design expert for the experiments. The power consumed and the cost were determined using GAMS Equations.

Table 2 Accomplishment of run designs

Run	H_2 injection%	Flow rate MMSCFD	Diameter inch	Power consumed, HP	Cost, MM $/ Yr.
1	5	400	28	13692	281
2	5	500	28	17658	392
3	5	600	28	26357	622
4	5	700	28	37683	990
5	5	800	28	68432	1807
6	10	600	30	21285	515
7	15	500	28	17987	403
8	15	600	28	26811	638
9	15	700	28	38259	1013
10	20	600	28	26157	616
11	5	600	36	11586	263
12	10	600	36	11706	266
13	20	600	36	11610	264
14	5	600	30	21106	508
15	10	600	30	21285	515
16	15	600	30	21550	522
17	20	600	30	21015	506

Results and Discussion

Modeling of hydrogen production and transportation

The compressors' power consumed, and the transportation cost were evaluated for various suggested runs. ANOVA technique generated models to analyze the relationships between process parameters and these key responses. To assess the quality and significance of these models, an analysis of variance (ANOVA) was conducted at a 95% confidence level, focusing on p-values and F-values. Both power consumed and cost models were best represented by the quadratic model. However, some terms within these models lacked statistical significance (p-values > 0.1). Therefore, the models were optimized by removing these insignificant terms, resulting in more concise and accurate representations of the process. Equations (7), (8) determine the power consumed and cost module. The results in table 3, 4 summarize the ANOVA analysis.

$$\text{Power consumed} = +1.38773 * 10^5 + 22.40522 * H_2\text{injection} - 347.61295 * \text{flow rate} - 1686.43565 * \text{Diameter} + 0.39368 * \text{flowrate}^2 \quad (7)$$

$$\text{Cost} = +3357.08361 + 36.53819 * H_2\text{injection} - 9.15343 * \text{flow rate} - 42.78792 * \text{Diameter} - 0.06 * H_2\text{injection} * \text{flowrate} + 0.010920 * \text{flowrate}^2 \quad (8)$$

Table 3 ANOVA Analysis results for the compressors power consumed response.

Sources	Sum of Squares	Mean Square	F-value	P-value	
Model	3.013E+09	1.004E+09	278.79	< 0.0001	significant
A-H_2 injection	2.345E+05	2.345E+05	0.0604	< 0.8100	
B-flow rate	1.869E+09	1.869E+09	518.90	< 0.0001	
C-Diameter	3.511E+08	3.511E+08	97.46	< 0.0001	
B^2	3.567E+08	3.567E+08	99.01	< 0.0001	
Residual	4.684E+07	3.603E+06			
Lack of Fit	4.684E+07	3.903E+06			
Pure Error	0.0000	0.0000			
Cor Total	3.060E+09				

Table 4 ANOVA Analysis results for the cost response.

Sources	Sum of Squares	Mean Square	F-value	P-value	
Model	2.327E+06	4.655E+05	372.76	< 0.0001	significant
A-H2 injection	135.32	135.32	0.1084	0.7482	
B-flow rate	3.562E+05	3.562E+05	285.24	< 0.0001	
C-Diameter	2.246E+05	2.246E+05	179.83	< 0.0001	
AB	6000.00	6000.00	4.81	0.0508	
B^2	2.359E+05	2.359E+05	188.95	< 0.0001	
Residual	13735.65	1248.70			
Lack of Fit	13735.65	1373.56			
Pure Error	0.0000	0.0000			
Cor Total	2.341E+06				

Statistical tests confirmed the chosen model's suitability for predicting compressors power consumed and transportation cost within the range of studied variables (A: H_2 injection, B: mixture flow rate and C: pipeline diameter). This was supported by high determination coefficients (R^2) for both models (0.9848 and 0.9941, respectively). These values indicate a strong fit between the model and experimental data, suggesting reliable predictions within the studied range.

Further validation came from comparing actual experimental results with model predictions for compressors power consumed and transportation cost Figures 3 and 4. The close agreement between the two demonstrates the model's accuracy and confirms the strong correlation between independent variables and the desired responses. Additionally, the high adjusted R^2 values (0.9797 for compressors power consumed and 0.9915 for transportation cost) provide further evidence of model robustness and minimize the influence of insignificant terms.

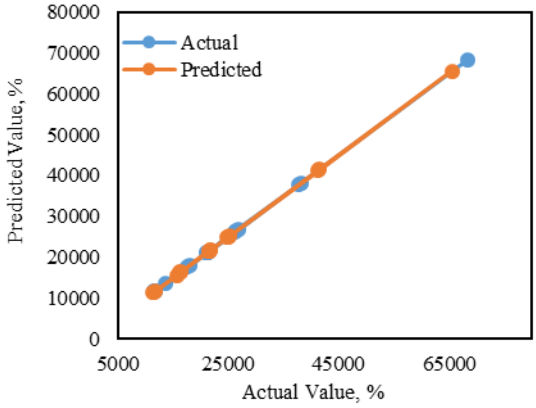


Figure 3 Actual vs predicted values for compressors power consumed.

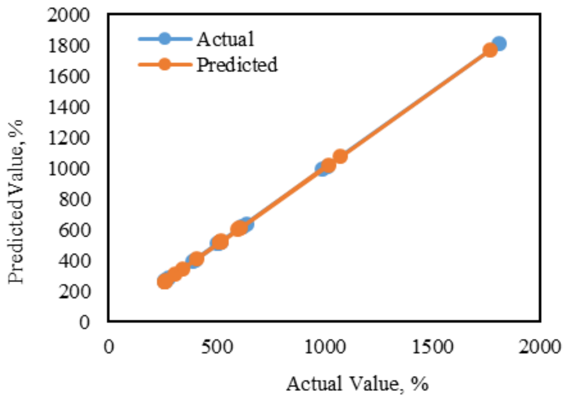


Figure 4 Actual vs predicted values for transportation cost.

Study of two affecting factor on Power consumption and transportation cost

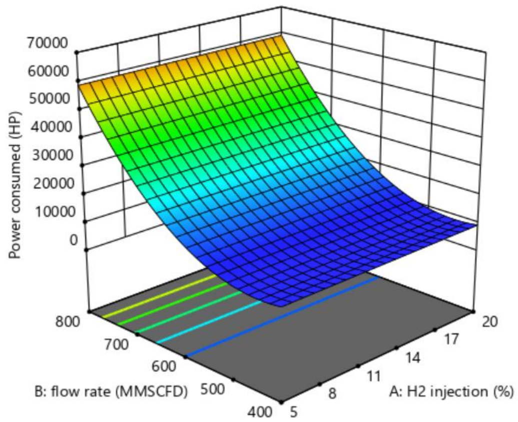
Understanding the intricate relationships between reaction parameters, as H_2 injection, mixture flow rate, and pipeline diameter is paramount for optimizing the best design. These factors exert a profound influence on both compressor power consumed and transportation cost, warranting a comprehensive examination for their synergistic effects.

Influence of mixture flow rate and H_2 injection percentage on Power consumption and transportation cost

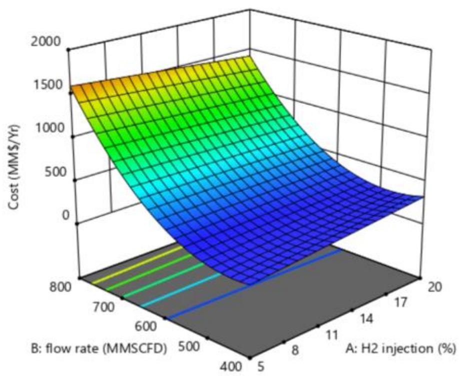
Figure 5 represent the effect of mixture flow rate and H_2 injection percentage on Power consumption and cost on a 3-D curve. The x- axis present the H_2 injection range from 5% to 20% and the z-axis present the mixture flow rate from 400 to 800 MMSCFD. As shown in figure 5.a, the increase in mixture flow rate at any given hydrogen injection percentage leads to an escalation in the power consumed by the compressors due to the higher demand for compression to maintain the flow within the system. However, As shown in figure 5.b Increasing the mixture flow rate at a low percentage of hydrogen (H_2) injection leads to an increase in transportation costs due to the additional energy required to maintain the flow, which results in higher operational expenses. When the mixture flow rate is increased alongside a higher percentage of hydrogen injection, the transportation costs decrease due to enhanced efficiency in conveying larger hydrogen quantities within the natural gas transmission network. This results in a reduction of the overall cost per unit of transportation, as the system becomes more adept at accommodating and transporting higher volumes of hydrogen, ultimately leading to improved cost-effectiveness in the transportation process.

Influence of the pipeline diameter and H_2 injection percentage on Power consumption and transportation cost

Figure 6 represent the pipeline diameter and H_2 injection percentage on Power consumption and cost on a 3-D curve. The x- axis present the H_2 injection range from 5% to 20% and the z-axis present the pipeline diameter from 28 to 36 inch. Figure 6, a showed that increasing the pipeline diameter, especially at various hydrogen injection percentage, generally decreases the power consumed.



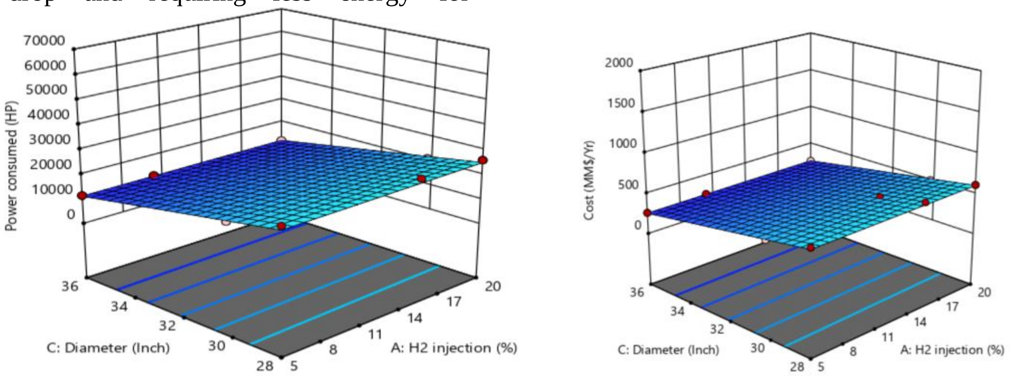
(a) Power consumed (HP)



(b) cost (MM$/Yr)

Figure 5 Effect of the mixture flow rate and H_2 injection percentage on Power consumption and cost

A larger diameter facilitates smoother flow, lowering frictional losses within the pipeline. This reduction in frictional losses results in less energy required for the transportation of hydrogen. The larger diameter allows for improved fluid dynamics, reducing resistance to flow and minimizing the overall pressure drop. This optimization is essential for enhancing the efficiency of hydrogen transport systems, contributing to energy savings and more economical operations in various industrial applications. Also, figure 6, b showed that increasing the pipeline diameter at different hydrogen injection percentage typically leads to decreased transportation costs. This is primarily attributed to the reduction in frictional losses and improved flow characteristics associated with a larger diameter. The larger conduit minimizes resistance to hydrogen flow, lowering pressure drop and requiring less energy for transportation. As a result, operational costs are reduced, contributing to more efficient and cost-effective hydrogen transport. Properly optimizing pipeline diameter is a crucial factor in enhancing the overall economic viability and sustainability of hydrogen transportation systems in various industrial contexts.

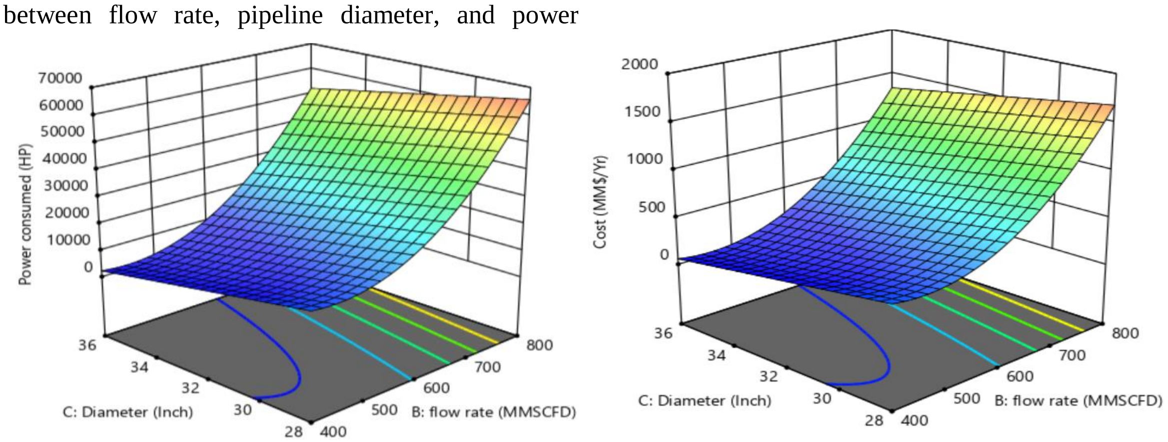


(a) power consumed (HP) (b) cost (MM$/Yr)

Figure 6 Effect of pipeline diameter and H_2 injection percentage on Power consumption and cost

Influence of pipeline diameter and mixture flow rate on the Power consumption and transportation cost

Figure 7 represent the mixture flow rate and pipeline diameter on Power consumption and cost on a 3-D curve. The x- axis present the mixture flow rate from 400 to 800 MMSCFD and the z-axis present the pipeline diameter from 28 to 36 inch. Figure 7.a showed that when the mixture flow rate increases in a pipeline with a decreasing diameter, the velocity of the mixture tends to rise. This results in higher frictional losses due to increased contact with the pipeline walls, leading to elevated pressure drop. The pump or compressor must work harder to overcome these additional losses, resulting in increased power. between flow rate, pipeline diameter, and power consumption in various industrial processes for efficient system design. Also, in Figure 7.b Increasing the mixture flow rate with a decreasing pipeline diameter can lead to higher transportation costs. The reduced diameter raises the fluid velocity, causing increased frictional losses and pressure drop. To maintain the desired flow rate, additional energy is required to overcome these losses, resulting in increased operational costs. Moreover, smaller pipelines may require more frequent maintenance and are prone to higher wear and tear, adding to maintenance expenses. Thus, optimizing pipeline diameter is crucial for minimizing transportation costs and ensuring efficient fluid transport in industrial applications.



(a) Power consumed (HP) (b) cost (MM$/Yr)

Figure 7 Effect of the pipeline diameter and mixture flow rate on Power consumption and cost

Study of three factors on Power consumption and transportation cost

Figure 8 showcases the interplay between the H_2 injection percentage, pipeline diameter and mixture flow rate on Power consumption and transportation cost. The x- axis presents the pipeline diameter from 28 to 36-inch, z- axis present the H_2 injection percentage from 5% to 20% and the y- axis present the mixture flow rate from 400 to 800 MMSCFD. Figure 8.a showed that decreasing the pipeline diameter while increasing the mixture flow rateat various hydrogen injection percentages tends to elevate compressor power consumption. The reduction in diameter results in higher fluid velocities, leading to intensified frictional losses and increased pressure drop. Compressors must exert more energy to overcome these heightened losses and maintain the desired flow rates. Consequently, this scenario not only demands more power from compressors but can also affect the overall efficiency of the hydrogen transport system. Careful consideration of the trade-offs between pipeline diameter, flow rates, and compressor power is essential for optimizing the performance and cost-effectiveness of such systems. Figure 8.b showed that decreasing pipeline diameter and hydrogen (H_2) injection percentage while increasing mixture flow rate can contribute to higher transportation costs. Smaller pipeline diameters may lead to increased frictional losses and pressure drop, necessitating more energy for fluid transport. Similarly, lower H_2 injection percentages could impact the overall efficiency of the transportation process. As the mixture flow rate rises, more power may be required from compressors or pumps, leading to increased operational expenses. Balancing these factors is essential for optimizing the design and operation of hydrogen transport systems to achieve both cost-effectiveness and efficiency.

Optimization Results

The optimization process aimed to obtain the optimal injection and flow rate ratio as well as the most suitable diameter for the transmission lines with minimum transportation costs and reduced energy consumption in the associated compressors using numerical optimization type. The optimal values of the three studied factors that the best design was determined.

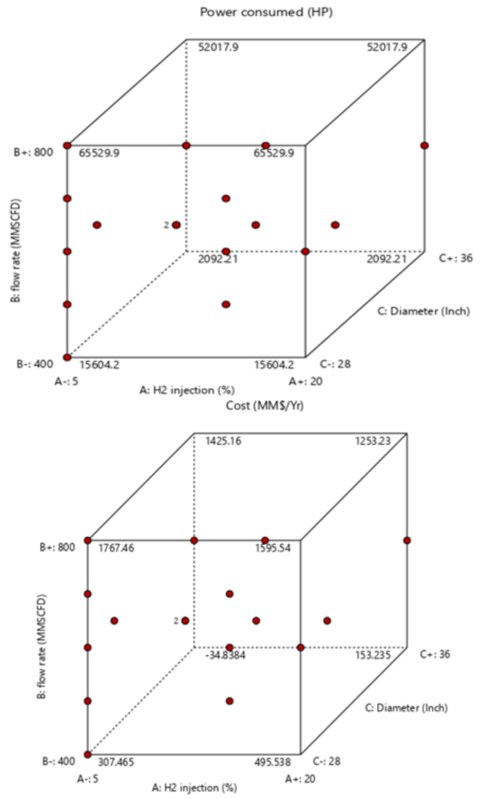


Figure 8 Effect of the H_2 injection percentage, pipeline diameter and mixture flow rate on Power consumption and cost

It was found that the best and minimum power consumption and transportation cost were **13831.097 HP and 314.673MMS/yr.,** respectively with desirability 87.1%. These values were achieved with H_2 injection percentage 20%, mixture flow rate 616.459 MMSCFD and pipeline diameter 36-inch as shown in Figure 9. The red dots in the figure indicate the optimal input factors values, while the blue color signifies the maximum outcome value**.**

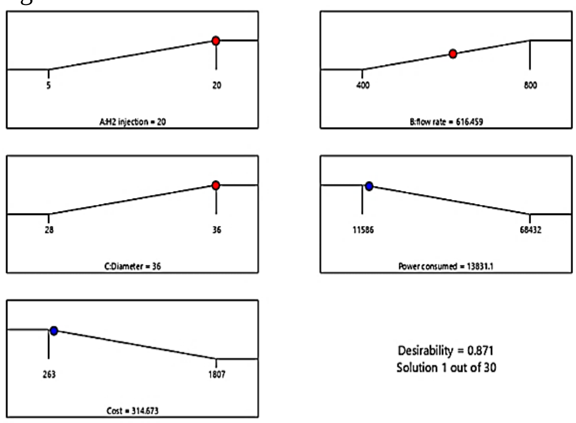


Figure 9 the optimal factors

Conclusions

Electrolysis emerges as a highly promising technique for generating substantial quantities of green hydrogen through the utilization of renewable electricity to electrolytically split water into hydrogen and oxygen. This sustainable method holds crucial significance in carbon emissions reduction, positioning electrolysis as a focal technology for large-scale green hydrogen production, especially when driven by renewable sources like wind or solar energy. Despite the benefits of utilizing green hydrogen as a renewable fuel, challenges arise in transporting it through pipelines, which are perceived as hazardous and associated with significant costs. Addressing these issues is the current focus of research, aiming to ensure both safety and cost-effectiveness.

Our research extensively explores the introduction of diverse hydrogen ratios into operational natural gas distribution networks, aiming to ascertain the ideal injection ratios and the corresponding costs through meticulous computational evaluations. The study leveraged advanced optimization software tools to achieve the most efficient outcomes. Mathematical formulations were integrated to compute energy consumption and the expenses linked to conveying hydrogen gas within the natural gas distribution network pipelines. The analysis and study of these calculations led to the identification of the lowest transportation cost and minimal energy consumption by compressors. The findings revealed that the best configuration resulted in a power consumption of 13831.097 HP and a transportation cost of 314.673 MM$/yr., with a desirability of 87.1%. These outcomes were achieved with a 20% H_2 injection percentage, a mixture flow rate of 616.459 MMSCFD, and a pipeline diameter of 36 inches.

Nomenclature

Parameter	**Identification**	**Unit**
T	Flow temperature	K
T_c	Critical temperature	K
P_c	Critical pressure	KPa
P_1	Upstream pressure	KPa
P_2	Downstream pressure	KPa
T_{avg}	The average temperature of gas	K
P_{avg}	The average pressure of gas	KPa
K	Specific heat ratio (Cp/Cv) is assumed to be 1.26	-
R	Universal gas constant	KJ/Kmol K
Z	Gas compressibility factor	-
P	The power required for compression process	Kw
CIP	Pipe investment cost	$/ year
R_P	Annual interest rate “12%”	-
C_p	Cost for a pipe/ diameter/ length “0.569”	$/in/ft
n	Life time of pipeline “20”	years
l,m,b	Non linearity constant obtained from regression “1, 1.428, 1.465”	-
CIC	Compressor investment cost	$/ year
C_{hp}	Compressor cost/ horse power “2000”	$/ hp
OC_{pipe}	Pipe operating cost	$/ year
C_{fp}	Fraction ratio of pipe operation cost to maintenance “0.2” (yearly maintenance cost)	-
OC_{comp}	compressor operating cost	$/ year
X	Is assumed to be 1.75	-
C_e	Electricity cost “0.055”	$/KWh
H_y	Operating time “8760”	Hours

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