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The Optimal Proportion for Blending Hydrogen with Natural Gas to Facilitate Its Utilization and Transportation Through the National Gas Transportation

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In Loving Memory of Late Professor Doctor ""Mohamed Refaat Hussein Mahran""

Abstract

This paper introduces a mathematical framework designed to model and evaluate natural gas pipeline networks with hydrogen infusion. Initially focusing on natural gas conveyance, the model is later expanded to accommodate hydrogen-natural gas blends. The optimization process is structured using a nonlinear approach within the General Algebraic Modelling System (GAMS) and fuzzy multi-criteria decision making (FMCDM). The research investigates the adaptation of current natural gas transmission networks to enable the conveyance of hydrogen-natural gas mixtures. Motivated by proposals to integrate renewable hydrogen into existing natural gas pipeline systems, the study aims to reduce dependency on fossil fuels within energy systems. The primary results highlight that a 1% hydrogen infusion yields the lowest cost (112 M$/year).

Keywords: GAMS, Hydrogen, Mathematical Model, Optimization.

1 Introduction

The world is facing a critical juncture in its energy landscape, as the scarcity of fossil fuels and the urgency to mitigate climate change through cleaner energy sources necessitate a transformative shift in energy policy [1, 2]. In response, renewable energy sources such as solar, wind, geothermal, ocean, biomass, nuclear, and hydrogen are being harnessed to reduce our reliance on fossil fuels [3, 4, 5]. Hydrogen, with its potential to act as a carbon-neutral energy carrier, stands out as a particularly promising solution [6]. Its capacity to store and distribute substantial energy quantities positions it as a crucial element in the shift toward a low-carbon economy. Nevertheless, the energy-intensive nature of hydrogen production necessitates methods such as methane steam reforming, water electrolysis, and biomass and coal gasification [7].

On the other hand, Natural gas as a non-renewable resource, offers a cost-effective and lower-emission alternative to other fossil fuels, serving as a bridge to a future dominated by renewable energy [8]. Its role as a transitional fuel is further enhanced by its compatibility with hydrogen, which, when blended with natural gas, can increase the renewable content of natural gas systems and contribute to a more sustainable energy future [9].

Pipelines, the traditional backbone of natural gas transportation, are poised to play a vital role in this transition, as innovation in hydrogen supply chains and end-use applications continues to expand [10]. As the world moves towards a hydrogen economy, the challenges of energy storage and sustainability are being met with novel solutions that are both efficient and environmentally responsible [11]. One of the initial research efforts has shown that it is feasible to transport a blend of Hydrogen and Natural gas (H-NG) through the existing natural gas grid, provided that the proportion of Hydrogen is relatively low in mass [12]. Incorporating hydrogen into established natural gas pipeline networks is a crucial move in realizing a more sustainable and effective energy infrastructure. As the world shifts towards renewable energy sources, the imperative to smoothly integrate

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hydrogen into the present natural gas grid is growing more apparent [13]. This integration not only requires a comprehensive understanding of the technical aspects of blending hydrogen with natural gas but also demands a strategic approach to optimize the pipeline configuration for minimal power consumption and cost-effective transportation [14,15]. In addressing this complex challenge, the utilization of advanced modeling techniques, particularly the General Algebraic Modeling System (GAMS), offers a powerful framework for analyzing and optimizing the blending of hydrogen in natural gas pipelines. Furthermore, the incorporation of a fuzzy approach to multi-criteria decision-making provides a robust method for handling the inherent uncertainty and imprecision associated with various factors involved in the optimization process [16,17].

This study seeks to investigate the modeling and enhancement of hydrogen blending with various concentrations in natural gas pipeline transmission networks by utilizing GAMS and a fuzzy multi-criteria decision-making method. The main goal is to pinpoint the best pipeline setup that lowers power usage while reducing overall transportation costs. By combining sophisticated modeling methods with a fuzzy multi-criteria decision-making framework, this investigation aims to tackle the complexities of optimizing hydrogen blending in natural gas pipeline networks, ultimately aiding in the advancement of more efficient and economical energy transmission systems.

2 Material and method

2.1 Material

2.1.1 Hydrogen and natural gas

Hydrogen and natural gas are pivotal materials in the context of energy production, transmission and distribution, each offering unique characteristics and advantages within the energy landscape [14]. Hydrogen is gaining significance as a clean and versatile energy carrier, holding potential as a key component in the transition to a low-carbon economy. Its ability to be produced through various renewable sources, such as electrolysis using renewable electricity, makes it an attractive option for sustainable energy storage and transportation [18]. As a material, hydrogen possesses high energy content per unit mass, making it an efficient fuel for various applications[18, 19]. It is also characterized by its clean combustion, as it produces water vapor as the only byproduct when used in fuel cells or combustion processes [21].

While natural gas plays a critical role in the global energy mix, serving as a relatively cleaner-burning fossil fuel compared to coal and oil [22]. Its abundance and widespread availability make it an essential energy source for heating, electricity generation, and industrial processes [23]. Moreover, natural gas serves as a transitional fuel in the shift towards renewable energy sources. It is primarily composed of methane, which contributes to its relatively lower carbon intensity compared to other fossil fuels. Its physical properties, such as high energy density and ease of storage and transportation, make it a versatile and valuable energy resource [24]. When considering the blending of hydrogen with natural gas in pipeline transmission networks, understanding the specifications and importance of both materials becomes crucial as shown in Table 1. This knowledge forms the basis for evaluating the technical, economic, and environmental implications of integrating hydrogen into natural gas infrastructure. Additionally, these considerations are essential for modeling and optimizing the blending process, as they provide insights into the behavior and interactions of hydrogen and natural gas within the pipeline network [10].

Table 1. The characteristics of hydrogen and methane, which is the primary component of natural gas from a physical standpoint [17, 25]

Parameters	Hydrogen (H2)	Methane (CH4)	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 (Cp/Cv)	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

2.1.2 Pipeline transmission network

A pipeline transmission network is a vital part of the energy infrastructure, serving to transport substances like oil, natural gas, and petroleum products over long distances. It comprises interconnected pipelines, compressor stations, and other facilities to move resources from production areas to refineries, distribution centers, and end-users [27]. Key components include pipelines of varying sizes and materials, pumping or compressor stations for maintaining pressure, control and monitoring systems for oversight and optimization, maintenance and inspection facilities, interconnection points for transferring substances, and adherence to stringent regulatory standards for safety and environmental protection. These networks are crucial for supporting industrial, commercial, and residential energy needs, involving complex engineering, environmental considerations, and regulatory compliance[28].

Gas pipeline transmission networks can be structured using three common topologies: linear, branched, and cyclic. Linear networks are direct, point-to-point, used for transporting natural gas from production fields to distribution centers. Branched networks have a primary pipeline with secondary branches, allowing flexibility in directing gas flow. Cyclic networks form closed-loop systems, maintaining consistent pressure and flow. The choice of topology depends on factors like geographical layout, population distribution, industrial demand, and operational requirements, ensuring efficient, reliable, and flexible transportation [29].

2.2 Methods

2.2.1 General Algebraic Modeling system

The General Algebraic Modeling System (GAMS) is a valuable tool for optimizing the power and cost considerations of natural gas pipeline transmission networks[30]. When applied to this context, GAMS allows for the formulation and solution of complex optimization problems related to power consumption and cost efficiency [31]. In the optimization of natural gas pipeline transmission networks, GAMS enables the development of mathematical models that can address various objectives, such as minimizing power consumption, reducing operational costs, or maximizing the overall efficiency of the network. These models can consider factors like pipeline routing, compressor station locations, pipeline diameters, and pressure levels to achieve the most energy-efficient and cost-effective configuration. By leveraging GAMS, engineers and analysts can create models that incorporate constraints related to power usage, operational costs, and network performance. These models can then be optimized to identify the most efficient and economical strategies for transporting natural gas through the pipeline network. Furthermore, GAMS facilitates scenario analysis, allowing for the exploration of different operational and investment strategies to optimize the power consumption and cost-effectiveness of natural gas transmission networks. This includes assessing the impact of infrastructure upgrades, changes in demand patterns, or the integration of renewable energy sources to enhance the overall efficiency and sustainability of the network. Ultimately, the application of GAMS in optimizing the power and cost considerations of natural gas pipeline transmission networks provides decision-makers with a powerful tool to improve the energy efficiency, cost-effectiveness, and overall performance of the network, aligning with environmental and economic objectives [32]. The optimization model comprises five essential elements [33]:

1. Sets, representing a grouping of nodes within the model.
2. Parameters encapsulating all variables of the model.
3. Variables, representing the components subject to change within the model.
4. Equations and their mathematical configurations, denoting the nomenclature and mathematical structure.
5. The model's inherent characteristics, such as its classification as a Mixed-Integer Nonlinear Programming (MINLP) model.

2.2.2 Fuzzy multi criteria decision making.

Fuzzy multi-criteria decision-making (MCDM) presents an effective method for optimizing the power and cost considerations of natural gas pipeline transmission networks [34]. This technique provides decision-makers to manage the intricacies and uncertainties inherent in the simultaneous evaluation of multiple criteria. When applied to the optimization of natural gas pipeline transmission networks, fuzzy MCDM facilitates the assessment of diverse factors, including power consumption, operational costs, environmental impact, reliability, and safety. By employing fuzzy sets to represent and handle imprecise or ambiguous information, decision-makers are able to integrate a range of, at times conflicting, criteria into the decision-making process [20]. Fuzzy MCDM methods enable the fusion of qualitative and quantitative factors, delivering a more extensive evaluation of the trade-offs involved in enhancing the power and cost efficiency of natural gas pipeline transmission networks. This approach allows for the inclusion of subjective judgments and expert opinions alongside quantitative data, contributing to a more holistic perspective in the decision-making process.

2.2.2.1 Fuzzy Approach Strategy

A decision is reached by evaluating all pertinent rules across various levels within a knowledge base. The assessments are conducted utilizing the MAX-MIN algorithm as per equation (1) [35].

$\mu_j(x) = \mathrm{Max}_{i\epsilon I}\{\mathrm{Min}_{N\epsilon N}\{\mu_{i1}(x_1), \mu_{i2}(x_2), \ldots, \mu_{iN}(x_N)\}$ (1)

Where:

μj (x): Represents the membership function of variable x in a fuzzy set corresponding to the selected rule to be activated at the jth level.

µiN(x): Denotes the membership function of variable x in a fuzzy set.

The MAX-MIN algorithm is executed in two phases: The MIN operation produces a set of truth values ($\boldsymbol{\lambda}$i) by evaluating the membership functions of all variables as shown in equation (2):

$\lambda_i(x) = \text{Min. } \{\mu_{i1}\ (x_1), \mu_{i2}\ (x_2), \ldots, \mu_{iN}\ (x_N)\}$ (2)

Subsequently, a single rule is selected by implementing the MAX operation according to equation (3):

$\lambda = \text{Max. } \{\lambda_1, \lambda_2, \ldots\ldots, \lambda_i\}$ (3)

In our multi-objective optimization study, the two rules by fuzzy quantities are represented in equation (4) embodying the following membership function:

- **Rule (1):** Maximization of gas line pack volume in the network.

$$\mu_1 = \begin{cases} 0 & f \leq fmin \\ \frac{f-fmin}{fmax-fmin} & fmax > f > fmin \\ 1 & f \geq fmax \end{cases} \quad (4)$$

- **Rule (2):** Minimization of power consumption and total transmission cost.

$$\mu_2 = \begin{cases} 1 & f \leq fmin \\ \frac{fmax - f}{fmax - fmin} & fmax > f > fmin \\ 0 & f \geq fmax \end{cases} \quad (5)$$

3 Pipeline mathematical model

A mathematical model addressing gas transportation in networks, accommodating various types of gases. This paper specifically delves into the study of natural gas and hydrogen mixtures. The required compression power for transmission is determined by the pressure drop in a gas pipeline, which has been obtained from the analysis of differential momentum balance. Energy losses due to friction between the fluid boundary layer and the interior surface of the tube lead to a reduction in gas pressure.

3.1 Gas compressibility factor

The compressibility factor (Z) is calculated using an equation of state Equation (6), 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 [36].

$$Z = 1 + 0.257\left(\frac{P_{avg}}{P_c}\right) - 0.533\left(\frac{P_{avg}}{P_c}\right)\left(\frac{T_c}{T_{avg}}\right) \quad (6)$$

3.2 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 (7,8) 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 [37]. The goal is to find an operational balance that maximizes energy efficiency and minimizes the overall environmental impact of the transmission system.

$$P = ZRT * \frac{Q}{Mw\ gas} * \left(\frac{k}{k-1}\right) * \left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right) \quad (7)$$

$$m_f = \frac{P_{shaft}}{\eta_i \eta_m \eta_d LHV} \quad (8)$$

3.3 Line pack maximization

In pipeline operations, the quantity of natural gas as it travels from the compressor's output pressure to the consumer's end-point pressure is crucial. Gas pipelines play a dual role, serving to transport natural gas from producers to consumers while also serving as storage facilities to maintain safety stocks. Equation (9) denotes the maximization of the line pack as a key aspect of this process.

$$V_b = 7.855 * 10^{-4}\left(\frac{T_b}{P_b}\right) * \left(\left(\frac{P_{avg}}{Z_{avg}T_{avg}}\right)D^2L\right) \quad (9)$$

3.4 Total cost minimization

The total cost will perform as the optimization process's objective function using equations (10-13) [38].

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

3.4.1 Pipe calculations

3.4.1.1 Pipe investment cost

$$CIP = \left(1 + R_p\right)C_pL^l d^m \frac{(1+r)^n r}{(1+r)^n - 1} \quad (10)$$

3.4.1.2 Pipe operating cost

$$OC_{pipe} = C_{fp}\frac{(1+r)^n r\,(1+R_p)C_pL^l d^m}{(1+r)^n - 1} \quad (11)$$

3.4.2 Compressor calculations

3.4.2.1 Compressor investment cost

$$CIC = C_{hp}\, HP^b \frac{(1+r)^n r}{(1+r)^n - 1} \quad (12)$$

3.4.2.2 Compressor operating cost

$$O\ C_{comp} = XE_{LC} \quad (13)$$

Where:

$X = 1 + C_{op}$

$E_{LC} = \frac{1}{8760} P_{Kwh}\, C_e H_y$

4 Case study

This study utilizes a simplified natural gas pipeline transmission network as a case study as shown in Figure 1, which comprises 8 nodes, including one source node and four demand nodes. The pipeline operates at a temperature of 298 K, and the injected hydrogen also operates at 298 K. Within this network, there is a branched flow of pure hydrogen along with co-flowing natural gas. The primary natural gas pipeline flow is represented as methane, and the hydrogen is aimed to achieve an average concentration ranging from 1% to 10%.

Each segment of the network exhibits distinct lengths with diameter of 36 inch. The pressure ranges from 1379 to 6895 kilopascals, while the necessary flow rate for delivery is 6 million standard cubic meters per day (MMSCMD).

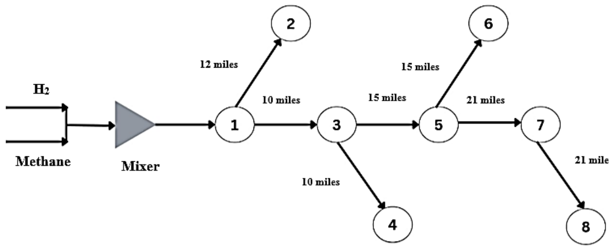

Figure 1. Simplified natural gas pipeline transmission network

5 Results and discussion

5.1 Results

We accurately determined the best quantity of compressors and their exact locations for the 36-inch system using GAMS. This analysis of primary objectives, encompassing line pack, fuel consumption, and power usage, was conducted using fuzzy logic and the specific calculations outlined in Table 2. By integrating these scientific approaches, we effectively identified the setup that provides the utmost configuration, as depicted in Figure 2.

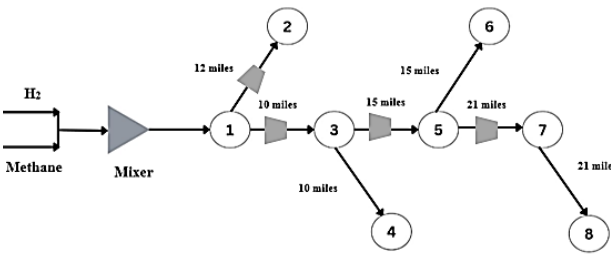

Figure 2. Pipeline network with the optimal location of compressor

Table 2 Results obtained through GAMS.

Hydrogen injection	Power (Hp)	Line pack (m^3)	Fuel consumption (Kg/S)
1%	7640	1717475	0.2
3%	7671	1710898	0.192
5%	7699	1704676	0.193
7%	7727	1698803	0.194
10%	7768	1690145	0.195

The normalization of every objective function using the Min-Max fuzzy approach is detailed in Table 3, wherein the smallest value of each row is identified in the "min" column, while the maximum of these minimum values is indicated in the "max" column.

Table 3. Normalization values by using Min-Max obtained through FMCDM.

Hydrogen injection	Power	Line pack	Fuel consumption	Min	Max
1%	1	1	1	1.00	1
3%	0.757812	0.759348	0.75	0.75	
5%	0.539062	0.531686	0.5	0.50	
7%	0.320312	0.316794	0.25	0.25	
10%	0	0	0	0.00	

The cost for each scenario was computed using equations (10:13) across different hydrogen injection concentrations. The objective was to identify the concentration that would result in the minimal cost while fulfilling the specified goals. Following extensive computations, it was established that the minimum cost aligns with the optimal injection, effectively achieving the desired goals. The primary findings are detailed in Table 3. The ultimate optimal outcomes indicate a hydrogen injection of 1% resulting in the lowest cost (112 M$/year).

Table 4. Relation between hydrogen injection and cost.

Scenario	Hydrogen injection	Cost (M$/Yr)
1	1%	112
2	3%	112.7
3	5%	113
4	7%	113.7
5	10%	114

5.2 Discussion

Our study successfully determined the optimal quantity and precise locations of compressors for the 36-inch system using GAMS, fuzzy logic, and specific calculations. By integrating these scientific approaches, we effectively identified the setup that provides the utmost configuration. This enabled us to pinpoint the concentration that would yield the lowest cost while meeting the specified objectives. Through extensive computations, we found that the minimum cost aligns with the optimal injection, effectively achieving our desired goals. These results are significant as they indicate that blending 1% hydrogen into natural gas pipelines is the most economical approach, with an estimated annual cost of 112 million USD. This discovery is crucial for informing energy policies and infrastructure planning, as it suggests a practical starting point for integrating renewable hydrogen into the existing energy system. By providing a viable starting point for the gradual integration of renewable hydrogen, our findings contribute to the ongoing efforts to establish sustainable and cost-effective energy solutions.

5.2.1 Effect of of H_2 concentration on power consmption

Figure 1 represents the relationship between the percentage of hydrogen (H_2) injection and power consumption. The study investigates a range of H_2 concentrations from 1% to 12% at constant flow rate 6 million standard cubic meters per day (MMSCMD) and diameter of 36 inch. Notably, the results indicate a direct correlation between increasing H2 concentration in the natural gas (N.G) pipeline and a subsequent rise in power consumption. The direct correlation between increasing H_2 concentration in the natural gas (N.G) pipeline and the rise in power consumption can be attributed to the chemical properties of hydrogen. As the concentration of hydrogen increases in the natural gas mixture, it alters the combustion characteristics, leading to a change in the energy release during combustion. This change in energy release directly impacts the power consumption, resulting in an observable increase as the hydrogen concentration rises.

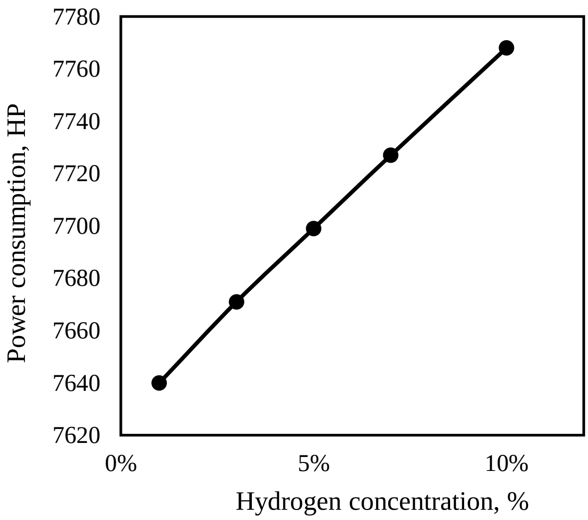

Figure 3. Influence of H_2 concentration on power consmption

5.2.2 Effect of H_2 concentration on the total cost

Figure 4 illustrates the connection between hydrogen (H_2) concentration and the overall cost. At constant flow rate 6 million standard cubic meters per day (MMSCMD) and diameter of 36 inch, the research delves into a spectrum of H_2 concentrations, ranging from 1% to 10%. The findings reveal a direct relationship, indicating that as the hydrogen concentration rises, there is a subsequent increase in the total cost. This suggests that higher concentrations of hydrogen lead to elevated overall costs. The marginal increase in costs from a 5% to 10% hydrogen injection, amounting to only 1.7%, suggests that the financial impact of higher hydrogen proportions within the natural gas pipeline network is minimal. This finding implies that there is potential to consider higher hydrogen infusion without encountering substantial cost escalation, thereby indicating that the economic implications may not hinder the integration of larger hydrogen proportions.

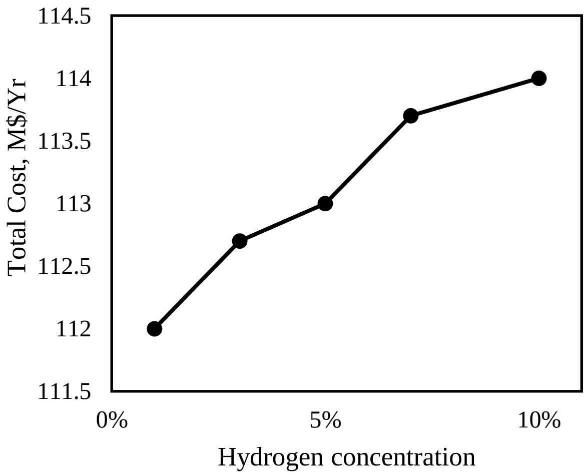

Figure 4. Influence of H_2 concentration on the total cost

6 Conclusion

The study presented a mathematical framework that is adept at simulating and assessing the performance of natural gas pipeline networks when integrated with hydrogen. The initial phase of the model addressed the transport of natural gas, which was subsequently extended to include the handling of hydrogen-natural gas mixtures. Optimization was carried out through a nonlinear methodology applied within the General Algebraic Modeling System (GAMS), supplemented by fuzzy multi-criteria decision-making (FMCDM) to navigate the complexities of decision-making under uncertainty. This research was driven by the objective of retrofitting existing natural gas pipelines to facilitate the transition towards mixed conveyance systems including renewable hydrogen, thereby decreasing reliance on purely fossil fuel-based energy infrastructures. Key findings revealed that incorporating a 1% hydrogen blend into the natural gas pipelines is the most cost-effective strategy, with an associated lowest cost of 112 million USD per year. This insight is significant for energy policy and infrastructure planning, suggesting a viable starting point for the gradual integration of renewable hydrogen into the energy mix.

Nomenclature

Parameter	Identification	Unit
γ_g	Gas specific gravity	-
T_b	Base temperature	K
P_b	Base pressure	KPa
P_1	upstream pressure	KPa
P_2	downstream pressure	KPa
T_f	Flow temperature	K
T_{avg}	The average temperature of gas	K
P_{avg}	The average pressure of gas	KPa
L	Pipe length	Km
D	Pipe diameter	mm
K	Specific heat ratio (Cp/Cv) is assumed to be 1.26	-
R	Universal gas constant	KJ/Kmol K
Mw_{gas}	Gas molecular weight	-
Z	Gas compressibility factor	-
LHV_i	Individual lower heating value	KJ/Kg
LHV	lower heating value of gas mixture	KJ/Kg
Q	Gas flow rate	Kg/s
P	The power required for compression process	Kw
m_f	is the mass flow rate of consumed gas as fuel for the compressor	Kg/s
η_m	Is the mechanical efficiency of compressor “0.9”	-
η_d	the driver efficiency of compressor “0.75:	-
η_i	Isentropic efficiency “0.8”	-
V_b	Line pack	MMCM
CIP	Pipe investment cost	$/ year
R	Annual interest rate “12%”	-
Cp	Cost for a pipe/ diameter/ length “0.569”	$/in/ft
N	Lifetime of pipeline “20”	years
l,m,b	Nonlinearity constant obtained from regression “1, 1.428, 1.465”	-
CIC	Compressor investment cost	$/ year
C_{hp}	Compressor cost/ horsepower “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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