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Inovações e Soluções Sustentáveis em Engenharia Ambiental

Model for utilizing Associated Natural Gas with hydrogen in Pre-Salt offshore explorations

Modelo de aproveitamento do Gás Natural Associado em hidrogênio nas explorações *offshore* do Pré-Sal

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ABSTRACT

In the race towards energy transformation, countless efforts are being made to improve efficiency and mitigate greenhouse gas emissions. In oil exploration and production (E&P), Natural Gas (NG) is a primary product exploited alongside crude oil due to its excellent energy potential. Under primitive conditions, NG can be classified as either Associated NG or Non-Associated NG. Non-Associated NG is produced from reservoirs containing almost exclusively dry gas, free of crude oil and water. Associated NG, on the other hand, is NG that is dissolved in oil or in contact with saturated crude oil. In Brazil, the NG produced from offshore reservoirs is predominantly Associated NG and, in addition to being exported, is used locally in power generation, artificial lifting and injected into reservoirs. This method is widely used in E&P to increase the recovery factor of reservoirs. The use of Associated NG is provided for in Resolution No. 806 of 2020 of the ANP (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis), which regulates the procedures for controlling NG losses and flaring. In E&P, since flaring is inevitable, it is proposed, with the NG currently used for flaring, to increase the utilization rate of Associated NG for hydrogen production through a modular structure suitably sized to fit the competitive space of a Floating Production Storage Offloading (FPSO) unit.

Keywords: Associated Natural Gas; Greenhouse gas; Floating Production Storage Offloading

RESUMO

Na corrida para a transformação energética, têm sido inúmeros esforços para melhorar a eficiência e mitigar as emissões dos gases com o efeito estufa. Na exploração e produção de petróleo (E&P), o gás natural (GN) é um produto primário explorado juntamente com o óleo bruto, devido ao seu excelente potencial energético. Nas condições primitivas, o GN pode ser classificado como GN Associado e GN Não Associado. O GN Não Associado é aquele produzido a partir de reservatórios quase que exclusivos de gás seco, livre de óleo bruto e água. Já o GN Associado é aquele que se encontra dissolvido no petróleo ou em contato com o óleo bruto saturado. No Brasil, o GN produzido a partir dos reservatórios offshore é predominantemente de origem associada e, além de exportado, é utilizado para consumo próprio, geração de energia elétrica, elevação artificial e injeção em reservatórios, método amplamente utilizado na E&P para aumentar o fator de recuperação dos reservatórios. A utilização do GN Associado está prevista na Resolução n°. 806 de 2020 da Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), que regulamenta os procedimentos de controle de perdas e queima de GN. Na E&P, uma vez que a queima é inevitável, propõe-se, com o GN atualmente utilizado na queima, aumentar o índice de utilização do GN Associado a produzir H2 através de estrutura modular adequadamente dimensionada a ocupar o concorrido espaço de uma *Floating Production Storage Offloading* (FPSO).

Palavras-chave: Gás Natural Associado; Gases do efeito estufa; Floating Production Storage Offloading

1 INTRODUCTION

The aim of this article is to model the reduction of flaring and loss of Associated NG in offshore E&P units. This objective is in line with the public policies of the CNPE (Conselho Nacional de Políticas Energéticas), presenting an innovative concept for the use of surplus offshore Associated NG.

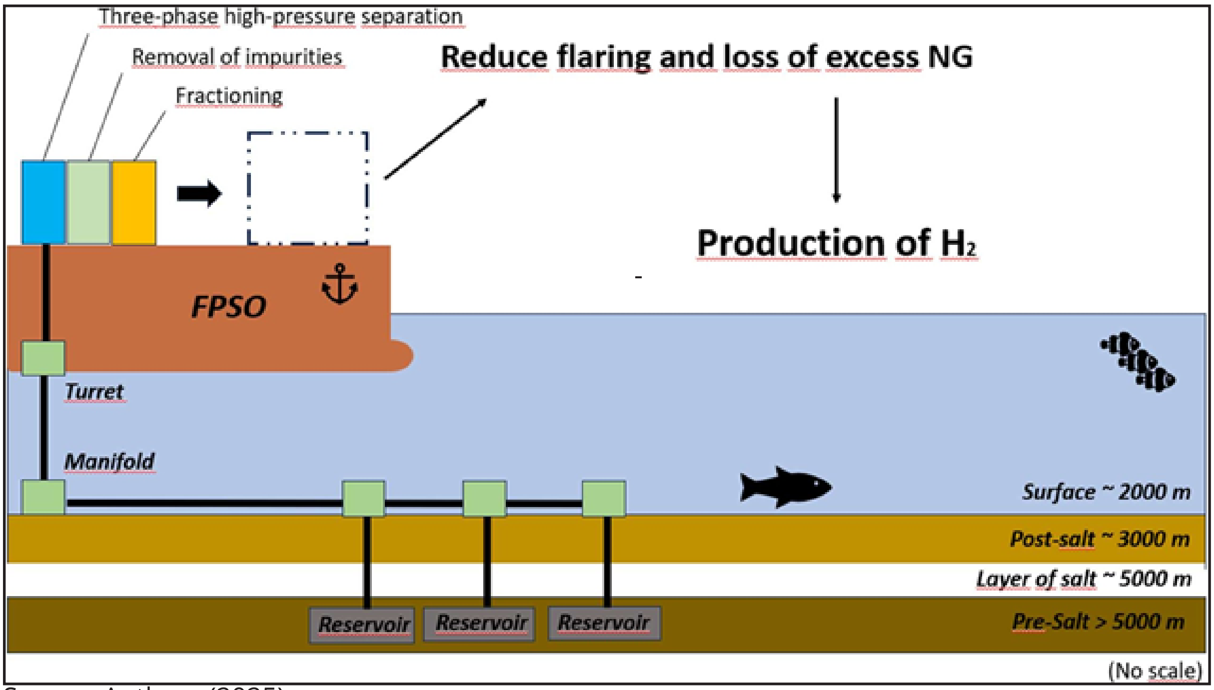
This article aims to evaluate offshore Associated NG as a source of energy and raw material to feed a modular offshore plant coupled to a FPSO unit for the production of hydrogen, Figure 1.

This system will provide a new alternative for E&P of surplus offshore Associated NG, in addition to those already being studied [1]. In other words, the aim is to reduce flaring and loss of this valuable resource by using it to produce hydrogen.

1.1 Framework

The flow of offshore Associated NG to the Natural Gas Processing Units, through pipelines, interconnected to storage and distribution terminals, and in tankers, is not enough to make full use of offshore Associated NG produce [1]. In practice, there are alternative uses, such as injection, artificial lifting and local consumption of NG to supply heat and electricity the FPSO unit.

Figure 1 – Pre-Salt E&P summary diagram (adapted from [1])



Source: Authors (2025)

1.1.1 Regulatory milestone

In 1997, Brazil established a regulatory framework for energy policy under Law No 9.478. This law created the CNPE and ANP, which are responsible for proposing national policies and specific measures for rational utilization of energy sources, including guidelines for the use of NG.

In 2000, ANP Ordinance No 249 regulated procedures for flaring and losses of oil and NG. This regulation received considerable attention and was recently updated by ANP Resolution No 806, establishing more stringent procedures for controlling and reducing flaring and losses. For maritime production, Resolution No 806 specifies that the flaring and loss of gas must correspond to a volume equal to or less than:

3% of the monthly NG production, not cumulative to any other reason of flaring or loss, carried out in an offshore production unit already in production or whose production begins within five years of the publication of Resolution No 806.

2% of the monthly movement of NG, not cumulative to any other reason for flaring or loss, carried out in a maritime production unit whose production begins at least five years after the publication of Resolution No 806.

1.5% of the monthly movement of NG, not cumulative to any other reason for flaring or loss, carried out in an offshore production unit that circulates or receives gas from other units in volumes equal to or greater thar 50% of the gas volume, or greater thar 50% of the volume of gas handled.

2 THEORETICAL BACKGROUND AND MATERIALS AND METHODS

The market committed to mitigating gas emissions views H2 production favorably because it effectively reduces greenhouse gas emissions.

2.1 Hydrogen gas

Hydrogen is a promising solution that can play a significant role in the world's leading energy matrix due to its high energy per unit weight. Compared to hydrocarbons, H2 has a higher energy potential since it is a lighter element and has a high carbon neutralization potential.

Because of this purpose, and taking advantage of the availability of methane in E&P, it is proposed to use it to produce H2 through the methane reformer system, thus increasing the utilization rate of the associated Natural Gas.

2.2 Steam Methane Reformer

Steam Methane Reforming (SMR) is the most widely used method in the industry for producing H2. It uses NG as a raw material and is responsible for an estimated 75% of the entire supply of global H2[2].

Initially, in the primary reformer, the processing of H2 through SMR technology occurs via a chemical reaction that transforms methane into H2, as represented by equilibrium equation (1):

$$CH_4 + H_2O \rightarrow CO + 3\,H_2, \qquad \Delta H^0_{298K} = 241{,}0\ kJ/mol \tag{1}$$

In the second and final stage, now subjected to an exothermic reaction that is independent of operating pressure, CO reacts on the Water-Gas Shift (WGS) catalyst to convert CO into CO2, while also producing a bit more H2. The chemical reaction for this transformation is represented in equilibrium equation (2):

$$CO + H_2O \rightarrow CO_2 + H_2, \qquad \Delta H^0_{298K} = -41{,}1\ kJ/mol \tag{2}$$

In the final stage of processing, the gases are transferred to the Pressure Swing Adsorption (PSA) unit, where H2 and carbon dioxide are separated using adsorption proprieties under high pressure and oscillation.

2.3 Carbon dioxide

Carbon Capture, Utilization, and Storage (CCUS) technology is a potential solution for a low-carbon energy production chain. Therefore, this scientific study proposes equipping the H2 processing system with devices fitted with CCUS technology. Approximately 9.01 kg of CO2 is generated for every kg of H2 produced using the SMR method [3], [4], [5], [6], [7], and [8], Table 1.

2.3.1 Carbon Capture, Utilization, and Storage

However, when coupled with CCUS systems, these emissions fall below 3.00 kg CO2 kg / 1.00 kg H2 [8] and [9]. Integrating CCUS technology with H2 production using SMR is a promising approach to reducing greenhouse gas emissions and establishing a low-carbon energy production chain.

Although the implementation of CCUS is still considered a high cost and an additional risk to Capital Expenditure, these costs have gradually decreased over the years [8]. Moreover, the environmental appeal makes these investments advantageous in terms of economic viability.

Table 1 – By-product of H2 processing by the SMR method

References	Carbon dioxide / H_2 (kg)
[4]	7,00
[5]	8,00
[7]	9,00
[8]	10,13
[3]	10,62

Source: Authors (2025)

The possibility of captured carbon dioxide being used as a miscible gas in injection into productive reservoir fields offers an operational advantage in E&P, as it aids in the displacement of the fluid.

Thus, it is also noteworthy that the concept proposed here is free from the need for logistics infrastructure and disposal for carbon dioxide. Once captured, the sequestered carbon dioxide should be injected as a miscible gas, returning it to the original reservoir.

3 MATERIALS AND METHODS

In April 2003, Chevron Texaco Technology Venture, one of the pioneers in the manufacturing of H2 processing systems, presented a prototype of an H2 processor derived from methane. At that time, the equipment had a production capacity of 7.2 m^3/h of H2.

Over the past two decades, the concept of H2 processing and storage systems has evolved significantly, and there are now dozens of manufacturers investing in the segment. Among them are those producing semi-constructed modular structures with a production capacity of up to 300 m^3/h.

Modular structures offer the advantage of operational testing directly on the assembly line, benefiting from the productivity of factory labor. Another advantage is the versatility to extend the equipment's lifespan, enhancing technical-economic feasibility indicators and allowing for potential expansions to accommodate future growth.

3.1 Modular structure concept

In January 2024, some of these manufacturers were consulted, including Hygear. The Hy.GEN 300 processor, available as a modular option in Hygear's portfolio and utilizing SMR, WGS, and PSA technologies, produces up to 300 Nm^3/h of H2 with a purity of 99.6.

This is the most suitable for the concept of this study due to its modularity, allowing for greater versatility.

4 METHODOLOGY AND PRELIMINARY RESULTS

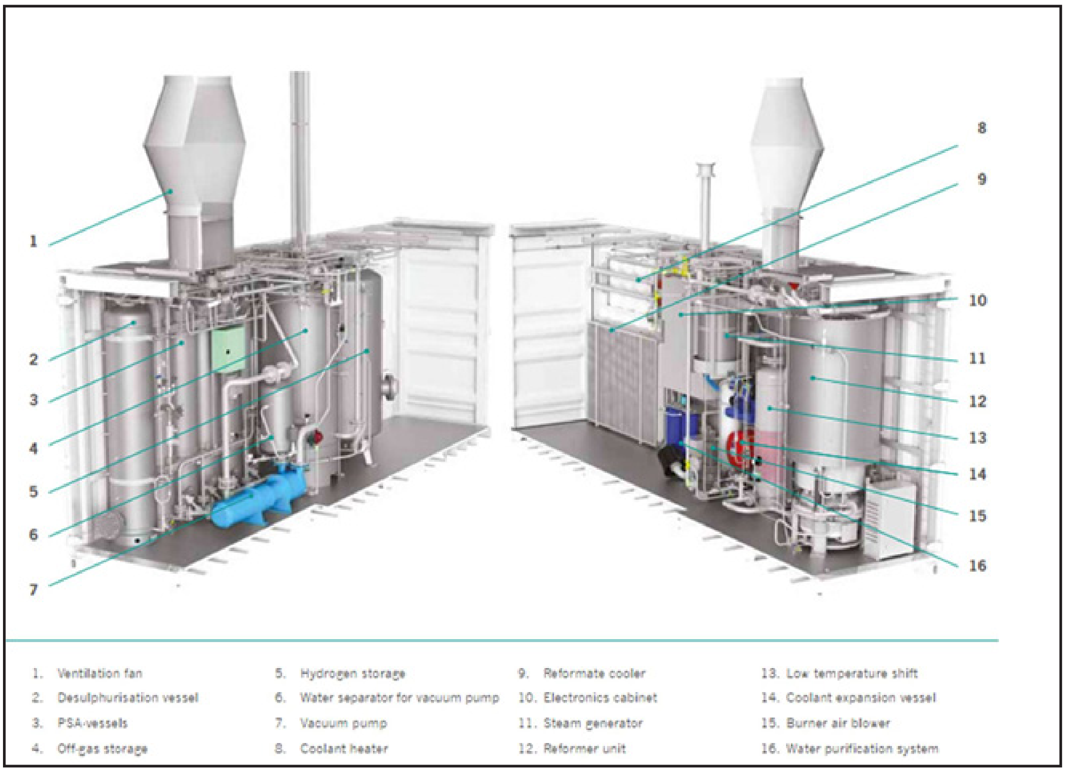
Initially, the methodology used to estimate the curve of flaring attenuation and loss of surplus gas was through collecting monthly historical data series released by the ANP [10], Figure 3.

The analysis of statistical data shows a peak in mid-2009, attributed to the start of the E&P campaign in the Brazilian Pre-Salt, during which authorities released their regulatory instruments and took measure to control the flaring and loss of NG.

Considering this, the series was divided into two distinct periods. The first period, from the start of the historical series until mid-2009, that shows heterogeneous behavior, was marked by scattered values of varying amplitudes and frequencies, which are difficult to explain.

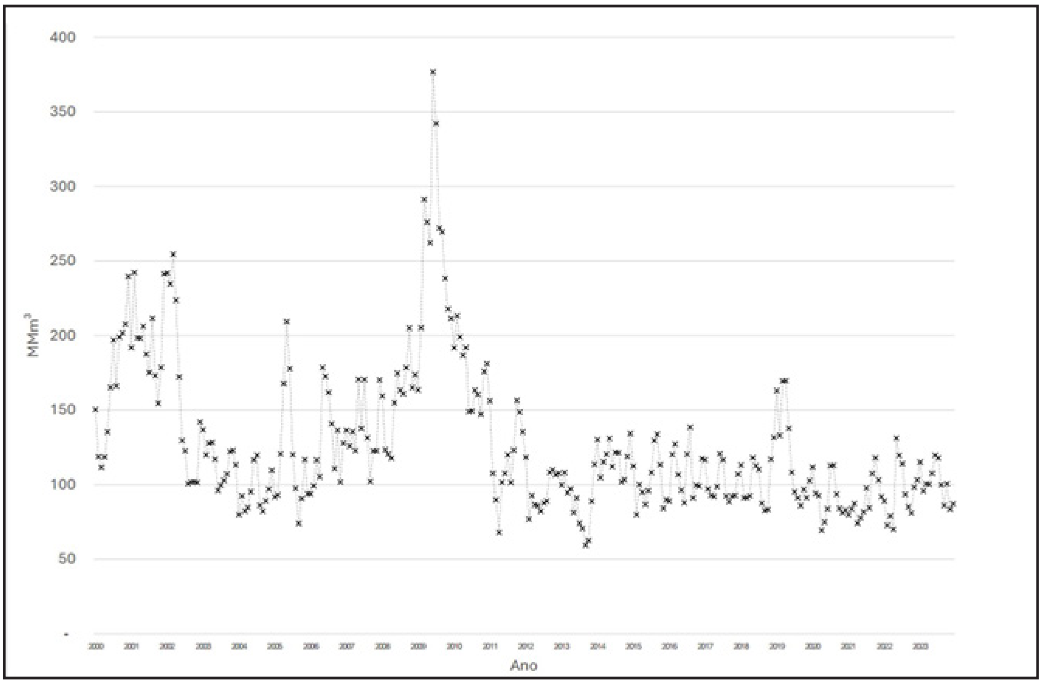
The second period, from mid-2009 to the end of 2023, is characterized by predominantly cyclical behavior, with rises and falls of similar amplitudes and characteristics, which allow a plausible explanation.

Figure 2 – Modular structure (by Hygear)



Source: Authors (2025)

Figure 3 – Historical series of NG flaring and loss



Souce: Authors (2025)

Based on this historical series, the central tendency data from descriptive statistics were analyzed, including mean, median, standard deviation, skewness, kurtosis, coefficient of variation, among others. These analyses showed a predominance of homogeneity from 2020 onwards, indicating a low incidence of influential outliers and a low probability of extreme values.

Consequently, the analysis of central tendency measure indicated that the percentage comparison between flaring and the loss of Associated NG with the production of Associated NG, demonstrates a more stable and monotonous behavior from 2020 onwards, which supports the prediction of stability to a steady state.

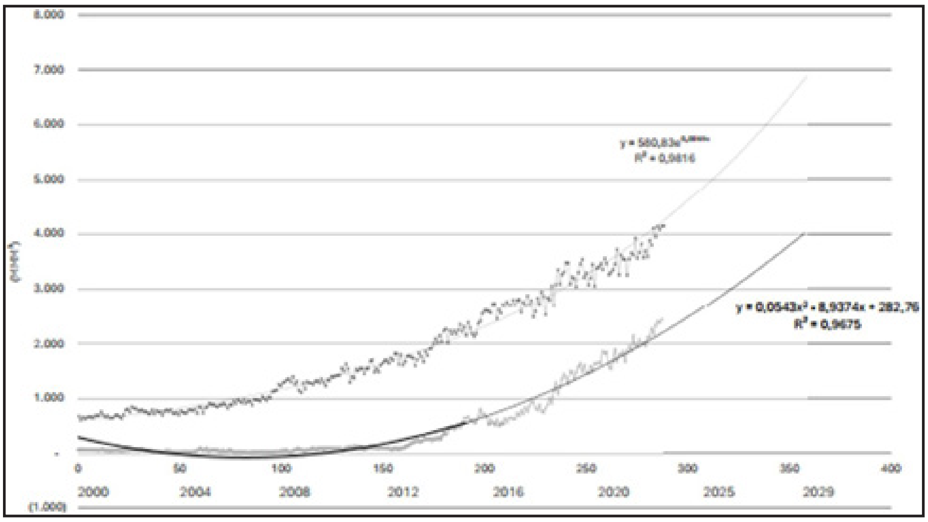
With these analyses explained by the statistical data and the trend toward a homogeneous normal distribution from 2020 onwards, this study confidently progresses to the stage of modelling trend functions using the statistical regression method.

With this data, the respective curves were then generated by identifying and using trend models extended to the coming decades. Next, equations were generated using non-linear regression, a widely used method to analyze data and estimates to verify statistical hypotheses [11], [12], [13] e [14].

These equations describe the relationships between the variables involved and their respective coefficients of determination, among other indicators (Figure 4).

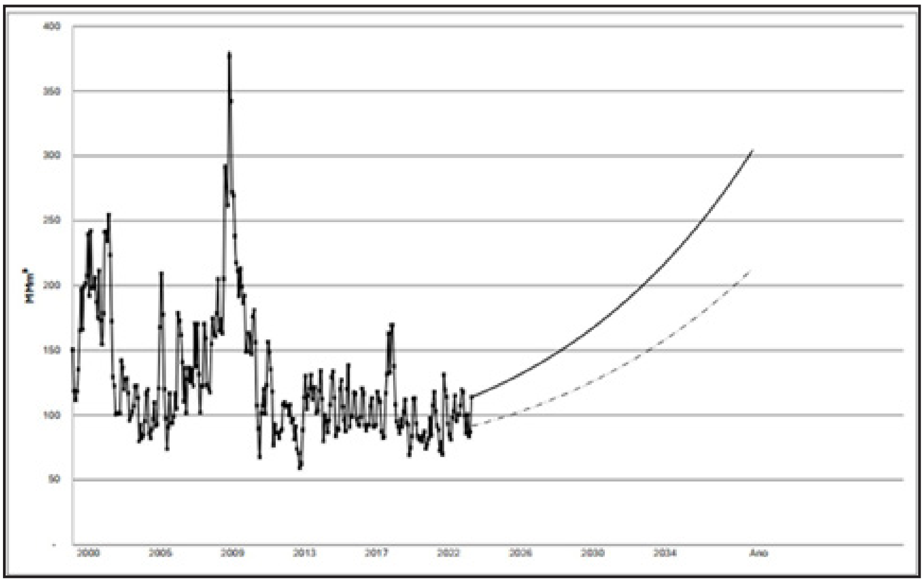
The non-linear regression method was used in the context of the growth curve because it sought to be a non-empirical and simple model whose parameters are interpretable. This method established a simple, functional relationship between production, injection burning, and loss in the time domain whose predictions could be extended beyond the observed data.

Figure 4 – Historical series of NG production and NG injection, as well as the respective non-linear regression method with the prediction of the curves for the coming years



Source: Authors (2025)

Figure 5 – The three curves are as follows: the historical series curve of NG flaring and loss from 2000 to 2023; the upper continuous curve representing the prediction model of NG flaring and loss if no action is taken; and the lower dashed curve representing the prediction model of NG flaring and loss simulating the increase in the NG utilization rate to feed multiple (fourteen) Hy.GEN 300 processing systems



Source: Authors (2025)

Similarly, based on the consumption of methane needed to process hydrogen from a modular plant attached to an FPSO unit, the flaring and loss attenuation curve was estimated, increase the utilization rate of offshore Associated NG.

The conceptual flow for the construction and assembly of the modular hydrogen processing plant using the SMR, Water Gas Shift (WGS), and Pressure Swing Adsorption (PSA) methods, equipped with the CCUS concept, was based on published works [2] and supplier datasheets.

5 CONCLUSIONS

The consequences of excessive use of oil have led to environmental pathologies that could be irreversible.

In the face of the inevitable flaring and loss of natural gas in offshore exploration and production, the implementation of a decentralized system for processing hydrogen in FPSO becomes an attractive alternative for increasing the utilization rate of Associated NG. This approach offers a safe and reliable alternative to conventional supply, putting into practice a way of using surplus gas. Producing H2 through SMR depends on the availability of raw materials, which are abundant in the offshore E&P environment. The present concept introduces a model for utilizing the sterile portion of routine NG flaring to enhance its usage, leading to H2 production.

The selection of equipment, as shown in Figure 2, presents a viable technical solution to the inevitable routine flaring of Associated NG.

This concept, if equipped with complementary CCUS technology, will provide a permanent solution, paving the way toward carbon. With local carbon capture, the logistics and final disposal of the waste are eliminated. This solution also contributes technically to fluid displacement in the artificial lifting of crude oil.

In the last four years, the average NG flaring and loss rate was 2.68%. Based on the date, the prediction model estimates a reduction to 2% of NG production by 2035, 1.54% by 2050, and around 1% by the end of the century if no action of taken. However, queries and uncertainties persist regarding the achievement of carbon neutrality by 2050 and the total elimination of routine flaring in offshore production units by 2030.

This approach offers a secure and reliable technical solution, adapted to the offshore scenario, defending an additional method for utilizing Associated NG while promoting carbon neutrality.

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