Monetization of Stranded & Flare Gas

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Abstract: ***As global energy demands continue to escalate, the dependence on fossil fuels remains a critical factor in exacerbating environmental degradation, particularly through the emission of greenhouse gases. Conventional gas refuelling systems, which cater to both the transportation and stationary energy sectors, have become antiquated in their design, resulting in significant inefficiencies and perpetuating unsustainable environmental practices. This paper presents an in-depth exploration of advanced optimization strategies for gas refuelling solutions aimed at fostering a more sustainable and environmentally responsible future. The study begins by thoroughly examining the environmental and economic ramifications of traditional refuelling infrastructures, highlighting key inefficiencies and their substantial contributions to global pollution levels. It also underscores the urgent need for a transition to cleaner technologies. The paper delves into emerging alternatives, such as the use of hydrogen, biogas, and other renewable energy sources, which offer promising pathways to reduce dependency on fossil fuels and mitigate harmful emissions. Moreover, critical optimization methodologies are analysed in detail, including the application of data-driven management systems, state-of-the-art fuel delivery technologies, and energy recovery processes. These innovations demonstrate considerable potential in enhancing refuelling efficiency, lowering operational costs, and significantly reducing environmental footprints. The integration of these advanced systems with existing infrastructures is examined to provide a holistic understanding of how these solutions can contribute to achieving global sustainability goals. In light of evolving international regulatory frameworks, this paper also highlights the pivotal role of policy intervention and technological innovation in driving the adoption of cleaner and more efficient refuelling systems. A series of case studies is presented to showcase real-world implementations, including the optimization of liquefied natural gas (LNG) refuelling processes and the deployment of hydrogen refuelling stations. These case studies illustrate the tangible benefits of adopting optimized refuelling systems, providing valuable insights into their scalability and long-term viability. The paper concludes by offering strategic recommendations for future research and development initiatives aimed at advancing sustainable refuelling infrastructures. By advocating for the integration of renewable energy sources into refuelling systems and promoting cross-sector collaboration, this paper argues that such advancements are essential for the transition to a cleaner, more sustainable energy future.***

Keywords: sustainable refueling, renewable energy, fossil fuel alternatives, hydrogen refueling, environmental optimization

1. Introduction

1.1 Background and Motivation

The global energy landscape is undergoing a significant transformation due to increasing concerns over climate change, resource depletion, and energy security. Despite the growing adoption of renewable energy sources, fossil fuels continue to dominate the energy mix, particularly in the transportation sector, where gasoline, diesel, and natural gas remain primary fuels. This dependency has resulted in large-scale environmental challenges, most notably greenhouse gas emissions that contribute to global warming.

The traditional gas re-fuelling infrastructure, while effective at meeting current demand, presents numerous inefficiencies and challenges from a sustainability perspective. Gas stations and refuelling facilities around the world are responsible for significant carbon emissions—not just through fuel combustion, but also via the energy-intensive processes of extraction, transportation, and distribution. Furthermore, the infrastructure itself, including pipelines, storage tanks, and transportation methods, contributes to environmental degradation through leaks, spills, and inefficiencies.

1.2 The Challenge of Sustainability

A major challenge in achieving a sustainable future lies in optimizing existing gas re-fuelling systems while simultaneously reducing the dependence on fossil fuels. With global climate agreements, such as the Paris Agreement, setting ambitious targets for emissions reduction, there is an urgent need to rethink how refuelling solutions can align with these goals. The current re-fuelling infrastructure, which is largely designed around fossil fuels, is not equipped to support emerging clean energy sources such as hydrogen or biofuels without significant modifications.

Additionally, the growing demand for fuel, driven by population growth and increasing industrial activity, places further strain on the refuelling infrastructure. These factors underline the necessity for optimizing refuelling processes to improve energy efficiency, reduce waste, and minimize environmental impact.

1.3 Scope of the Paper

This paper focuses on the optimization of gas re-fuelling systems through technological innovation, enhanced logistical frameworks, and supportive policy measures. Both traditional and alternative fuels are considered, with a special focus on refuelling systems for transportation and stationary energy applications. Key optimization strategies discussed include the integration of advanced materials for storage tanks, energy recovery during refuelling, and the use of data analytics to optimize fuel delivery systems.

Through the lens of sustainability, the paper examines how gas refuelling infrastructure can evolve to meet the demands of a low-carbon future. Particular attention is given to the role of hydrogen as a promising alternative to traditional fuels, as well as the potential of biogas and synthetic fuels to offer low-emission solutions.

1.4 Objective

The objective of this paper is to provide a comprehensive overview of current gas refuelling systems and present optimization strategies that can reduce environmental impacts while improving economic feasibility. The research aims to bridge the gap between existing technologies and emerging sustainable alternatives, offering actionable insights into the design and operation of more efficient refuelling solutions. Ultimately, the paper aims to contribute to the global discourse on sustainable energy by identifying ways in which refuelling solutions can support both present and future energy needs in an environmentally responsible manner.

2. Environmental and Economic Impact of Traditional Gas Re-Fuelling Systems

2.1 Current Refuelling Infrastructure

The global gas refuelling infrastructure is vast and deeply entrenched, comprising networks of gas stations, pipelines, tanker trucks, and storage facilities. These systems serve millions of vehicles, industrial facilities, and power plants daily, ensuring uninterrupted fuel supply. Gasoline and diesel fuels dominate the refuelling landscape, with natural gas (compressed or liquefied) gaining traction in certain regions, especially in the commercial and heavy-duty vehicle sectors.

While this infrastructure is critical to meeting current energy demands, it has not been designed with sustainability as a core focus. The traditional refuelling model involves high levels of energy consumption, particularly during extraction, transportation, and distribution. Long-distance transportation of gas by tankers or pipelines, combined with the energy required for refining and processing, results in significant energy losses and carbon emissions.

2.2 Environmental Footprint

The environmental impacts of traditional gas refuelling systems are substantial, and they occur at various stages of the fuel life cycle:

- **Greenhouse Gas Emissions**: Fossil fuel combustion at the point of use (e.g., vehicles) is the most visible source of carbon dioxide (CO_2), but significant emissions also occur during the fuel production, refining, and distribution phases. For instance, methane (CH_4), a potent greenhouse gas, can leak from natural gas pipelines and storage facilities, contributing more significantly to global warming than CO_2 over a short-term horizon.
- **Air Pollution**: In addition to CO_2, refuelling systems contribute to the emission of nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM). These pollutants are harmful to human health and can lead to respiratory diseases, particularly in urban areas with high vehicle density.
- **Water and Soil Contamination**: Accidental fuel spills, whether during transportation or at refuelling stations, pose risks to water bodies and soil quality. Underground storage tanks (USTs), commonly used in gas stations, are prone to leaks, releasing gasoline and diesel into groundwater.
- **Energy Consumption in Distribution**: The energy used in transporting and dispensing fuel is non-negligible. For example, tanker trucks must often travel long distances to remote refuelling stations, consuming fuel themselves and increasing the system's overall energy demand.

2.3 Economic Factors

The economic challenges of maintaining the current gas refuelling infrastructure are multifaceted:

- **Capital Investments**: Maintaining and upgrading aging infrastructure, such as pipelines and storage tanks, requires significant capital expenditure. For instance, underground storage tanks require constant monitoring and periodic replacement to prevent leakage.
- **Fuel Losses**: Traditional refuelling systems are prone to losses due to evaporation, leaks, and spills. Such losses not only contribute to environmental degradation but also reduce profitability for fuel suppliers.
- **Operational Costs**: The energy required to transport, store, and dispense fuel represents a major operational cost. Additionally, fluctuations in fuel prices and supply disruptions can impact profitability and create economic uncertainty in the fuel distribution sector.

2.4 Sustainability Gap

The environmental and economic drawbacks of the current gas refuelling systems highlight a significant sustainability gap. Despite advances in fuel efficiency and emission controls for vehicles, the upstream aspects of the refuelling infrastructure remain largely unchanged. The reliance on fossil fuels, combined with inefficiencies in distribution and storage, makes it difficult for these systems to align with global sustainability goals. Optimizing these systems is essential not only to reduce emissions but also to improve economic viability in the long term.

3. Emerging Technologies in Gas Re-Fuelling

3.1 Innovations in Fuel Delivery Systems

Emerging technologies offer several pathways to optimizing gas refuelling systems. One key area of development is in fuel delivery, where automation and digitalization are making refuelling processes more efficient and less prone to human error.

- **Automated Refuelling Systems**: Automated fuelling systems, equipped with sensors and Internet of Things (IoT) technology, can monitor fuel levels and optimize the refuelling process. These systems allow for precise control of fuel dispensing, minimizing losses due to overfilling or evaporation. For example, smart fuelling stations equipped with automated pumps and leak detection systems have been shown to reduce emissions and fuel losses significantly.
- **IoT-Enabled Monitoring**: Advanced monitoring systems, driven by IoT technology, offer real-time insights into fuel tank levels, leakages, and fuel quality. This data-driven approach allows fuel distributors to optimize delivery routes, ensure timely refuelling, and prevent potential environmental hazards such as fuel leaks.

3.2 Advanced Materials and Design

The development of new materials for fuel storage and transportation systems is another area of technological advancement. These materials aim to reduce the risk of leaks,

Paper ID: SR241006134022 DOI: https://dx.doi.org/10.21275/SR241006134022

improve the durability of storage tanks, and enhance the safety of fuel transport.

- **Composite Storage Tanks**: Composite materials, such as carbon fibre-reinforced polymers, offer significant advantages over traditional metal storage tanks. These tanks are more resistant to corrosion, reducing the risk of fuel contamination and leakage. Additionally, they are lighter, which can reduce transportation energy costs.
- **Nanotechnology for Leak Prevention**: Nanomaterials are being explored to improve the sealing and insulation properties of fuel tanks and pipelines. For instance, nano-coatings can be applied to the interior of storage tanks, preventing fuel permeation and enhancing durability.

3.3 Hydrogen as an Alternative

Hydrogen is emerging as a viable alternative to traditional fossil fuels, particularly in sectors such as transportation and industry. Hydrogen refuelling infrastructure, though still in its nascent stage, holds significant potential for reducing carbon emissions.

- **Hydrogen Refuelling Stations**: Hydrogen refuelling technology is evolving rapidly, with several countries investing in hydrogen infrastructure to support fuel cell electric vehicles (FCEVs). Hydrogen can be stored in pressurized tanks or in liquid form, and it offers near-zero emissions when used in fuel cells. However, the challenge lies in the scalability of hydrogen production and distribution.
- **Comparison with Gasoline and Natural Gas Systems**: Hydrogen refuelling stations, while less polluting, face challenges related to cost and scalability. In contrast, natural gas refuelling systems are well-established but suffer from methane emissions and other environmental impacts. Hydrogen systems, if optimized, could offer a cleaner alternative, but require significant infrastructure investment.

3.4 Biogas and Synthetic Fuels

Biogas, derived from organic waste, and synthetic fuels, created through chemical processes, offer renewable alternatives to fossil fuels. Both of these options can be integrated into existing refuelling systems with some modifications, making them attractive options for sustainability.

- **Biogas Refuelling Systems**: Biogas can be used in compressed natural gas (CNG) vehicles with minor modifications to the fuelling infrastructure. This offers a low-carbon alternative to fossil fuels, especially in agricultural and waste management sectors.
- **Synthetic Fuels**: Synthetic fuels, produced from renewable energy sources, are gaining traction as a cleaner alternative to conventional gasoline and diesel. These fuels can be used in existing internal combustion engines (ICEs), reducing the need for new vehicle infrastructure while offering a carbon-neutral solution.

4. Optimization Techniques for Gas Re-Fuelling

4.1 Data-Driven Optimization

With the advancement of digital technologies, data-driven optimization is emerging as a key strategy for improving gas refuelling systems. Leveraging big data, artificial intelligence (AI), and machine learning (ML) techniques, fuel companies can optimize refuelling operations in real-time, reducing waste, enhancing efficiency, and lowering emissions.

- **Predictive Analytics for Fuel Demand**: By analysing historical data and real-time metrics, AI-driven systems can forecast fuel demand at specific stations and optimize delivery schedules. This just-in-time refuelling strategy minimizes fuel overstocking, reduces storage-related emissions, and optimizes the use of transportation resources. For example, fleet management systems can predict when vehicles will need refuelling based on driving patterns and fuel consumption rates, ensuring optimal refuelling schedules.
- **Route Optimization for Fuel Delivery**: AI-driven route optimization software can identify the most fuel-efficient delivery routes, factoring in traffic conditions, vehicle load, and road inclines. This reduces the overall fuel consumption of delivery trucks and minimizes emissions. Case studies have shown that companies using AI-based route planning have reduced fuel use by up to 20%, translating into lower operational costs and carbon footprints.
- **Real-Time Monitoring and IoT Integration**: IoT devices, such as smart sensors installed in fuel tanks and pumps, enable real-time monitoring of fuel levels, pressure, and temperature. These devices can communicate data to central control systems, allowing fuel companies to detect anomalies (such as leaks or evaporation) and address them immediately. This approach improves operational efficiency and significantly reduces fuel losses.

4.2 Improved Efficiency in Transportation Logistics

The optimization of transportation logistics is another critical component of enhancing gas refuelling systems. Fuel transportation, whether via pipelines, tanker trucks, or ships, is energy-intensive and contributes to emissions. Several optimization strategies can be employed to reduce the environmental and economic impact of fuel transport.

- **Fleet Management Systems**: Advanced fleet management systems, equipped with GPS and IoT technologies, allow companies to monitor and manage fuel transportation in real time. These systems can optimize delivery routes, reduce vehicle idling times, and track fuel consumption, leading to more efficient logistics operations.
- **Fuel-Efficient Vehicles**: Fuel transportation companies are increasingly investing in fuel-efficient and hybrid vehicles to reduce the carbon footprint of their operations. Electric or hybrid tanker trucks, for example, can significantly reduce emissions associated with fuel delivery. Additionally, aerodynamic designs and lightweight materials in trucks can further improve fuel efficiency.

- **Just-in-Time Delivery Methods**: In conventional fuel supply chains, storage facilities often keep large fuel reserves on hand, which can result in higher evaporation losses and require more energy for temperature control. Just-in-time delivery methods, where fuel is delivered exactly when needed, reduce storage times and minimize fuel losses. This approach requires precise demand forecasting and real-time monitoring of fuel levels, both of which can be achieved through data analytics.

4.3 Energy Recovery Systems

Another promising approach to optimizing gas refuelling systems is the integration of energy recovery technologies. These systems aim to capture and reuse energy that would otherwise be wasted during the refuelling process.

- **Waste Heat Recovery**: During the compression and liquefaction of gases such as natural gas or hydrogen, a significant amount of heat is generated. Waste heat recovery systems can capture this excess heat and convert it into electricity or use it to power auxiliary systems. This can reduce the overall energy consumption of refuelling stations and contribute to lower operational costs.
- **Energy-Efficient Pumps**: Fuel pumps used in refuelling stations are typically powered by electricity, and optimizing their energy efficiency can result in significant cost and energy savings. Advanced pump designs, such as variable-speed pumps, can adjust power consumption based on the actual flow rate needed, minimizing energy waste during low-demand periods.
- **Pressurized Refuelling**: Pressurized storage and refuelling systems reduce fuel evaporation losses by maintaining fuels like natural gas or hydrogen in a compressed state. By keeping these fuels under higher pressure, energy losses during the transfer process are minimized, enhancing overall system efficiency.

4.4 Reduction of Fuel Losses

Minimizing fuel losses during transportation, storage, and dispensing is critical for improving both the environmental and economic performance of refuelling systems. Several technologies and practices can help reduce fuel losses.

- **Pressurized Storage Tanks**: Pressurized storage tanks are commonly used in the storage of liquefied natural gas (LNG) and hydrogen, as they help maintain the fuel in a stable, compressed state, minimizing evaporation losses. By reducing the volatility of the stored fuel, pressurized tanks reduce the risk of leaks and emissions during storage and dispensing.
- **Leak Detection Systems**: Advanced leak detection systems, using sensors and real-time monitoring, can identify even minor leaks in fuel tanks and pipelines. By detecting leaks early, these systems prevent fuel loss and mitigate environmental risks. Modern leak detection technologies can also be integrated with IoT systems to trigger automatic alerts and shutoffs in case of leakage.
- **Fuel Vapor Recovery**: Vapor recovery systems capture and recycle the fuel vapours that escape during the refuelling process. These systems are especially useful at gas stations, where significant amounts of gasoline vapor are lost into the atmosphere. By recovering these vapours and condensing them back into liquid form, vapor recovery systems reduce fuel losses and emissions of volatile organic compounds (VOCs).

5. Regulatory and Policy Frameworks Supporting Sustainability

5.1 Global Emission Standards

International agreements and national regulatory frameworks are playing a critical role in driving the optimization of gas refuelling systems. Various emission standards, such as those set by the Kyoto Protocol, the Paris Agreement, and national regulations like the U.S. Environmental Protection Agency (EPA) guidelines, aim to limit greenhouse gas (GHG) emissions and reduce the environmental impact of fuel production, distribution, and consumption.

- **The Paris Agreement**: The Paris Agreement, signed by nearly every nation, set the stage for aggressive reductions in global carbon emissions. By establishing national targets for emission reductions, the agreement has created incentives for countries to innovate and invest in cleaner fuel technologies and optimized refuelling systems.
- **EPA Regulations**: In the U.S., the EPA's Clean Air Act imposes strict limits on emissions from stationary and mobile sources, including fuel distribution networks. These regulations push fuel distributors and refuelling stations to adopt advanced leak detection systems, vapor recovery technologies, and cleaner fuel alternatives, such as natural gas and hydrogen.

5.2 Incentives for Clean Refuelling Solutions

Government policies around the world are increasingly providing financial incentives to promote cleaner refuelling technologies. These incentives are designed to accelerate the transition to sustainable refuelling infrastructure.

- **Tax Breaks and Grants**: Many governments offer tax incentives and grants for the installation of hydrogen refuelling stations, electric vehicle (EV) charging infrastructure, and LNG facilities. For instance, the European Union has implemented several funding programs to support the expansion of alternative fuel networks.
- **Carbon Credits**: Carbon markets allow companies to earn credits by reducing their emissions, which can then be traded or sold. Fuel companies that optimize their refuelling systems, reduce leaks, or switch to cleaner fuels can earn carbon credits, creating an economic incentive to adopt sustainable practices.

5.3 International Collaboration

The optimization of gas refuelling systems requires cross-border collaboration, especially as the global energy market becomes increasingly interconnected. International bodies such as the International Energy Agency (IEA) and the United Nations Framework Convention on Climate Change (UNFCCC) are working to harmonize standards and promote best practices for sustainable fuel distribution.

- **Standardization of Refuelling Infrastructure**: International organizations are working to standardize refuelling infrastructure, especially for emerging fuels like hydrogen. These efforts ensure that new refuelling stations are compatible across borders, making it easier for countries to adopt cleaner refuelling technologies.

- **Technology Transfer**: Developing countries often lack the resources to invest in advanced refuelling infrastructure. International collaboration through technology transfer programs allows these countries to adopt optimized systems at lower costs, contributing to global emissions reductions and improved sustainability.

6. Case Studies of Optimized Gas Re-Fuelling Systems

Case Study: Natural Gas Purification – Removal of CO2, N2, Water Vapor, and Heavy Hydrocarbons

1) Introduction

Natural gas is a widely used energy source globally, serving multiple industries from power generation to heating and transportation. However, raw natural gas extracted from underground reservoirs is rarely pure; it contains various contaminants that reduce its efficiency, pose operational risks, and lower its market value. These contaminants include carbon dioxide (CO2), nitrogen (N2), water vapor, heavy hydrocarbons, and hydrogen sulphide (H2S).

The presence of these impurities can lead to several problems:

- **Corrosion**: When CO2 and water combine, they form carbonic acid, which corrodes pipelines and equipment.
- **Energy Inefficiency**: Nitrogen and CO2 dilute the calorific value of natural gas, reducing its energy content.
- **Operational Hazards**: Water vapor can condense and form hydrates, causing blockages in pipelines, while heavy hydrocarbons can condense into liquids, affecting gas flow.

Purification of natural gas is critical to ensure that it meets the commercial standards required for pipeline transmission and consumption. This case study delves into the various technologies used to remove key impurities, including CO2, N2, water vapor, and heavy hydrocarbons, and presents real-world examples of how these technologies are applied in industry.

2) Problem Definition: Common Contaminants in Natural Gas

a) Carbon Dioxide (CO2):

- CO2 is an acid gas that reduces the energy content of natural gas. When combined with water, it forms carbonic acid, leading to pipeline and equipment corrosion.
- It is also a greenhouse gas, and its release contributes to climate change.

b) Nitrogen (N2):

- Nitrogen is an inert gas that dilutes natural gas, reducing its energy density.
- High levels of nitrogen in natural gas reduce its heating value, which can affect downstream processes and customer usage.

c) Water Vapor:

- Water vapor can form hydrates under high pressure and low temperatures, leading to blockages in pipelines.
- Additionally, water vapor combined with CO2 creates corrosive environments within pipelines and processing equipment.

d) Heavy Hydrocarbons:

- Heavy hydrocarbons like pentane, hexane, and heavier molecules can condense into liquids during transportation, potentially leading to flow restrictions in pipelines.
- These hydrocarbons also lower the gas's calorific value and are undesirable in the pipeline gas stream due to their tendency to form liquids under pressure.

These contaminants must be removed to meet pipeline specifications, maximize energy content, prevent equipment corrosion, and mitigate environmental impacts.

3) Purification Technologies for Natural Gas

a) Carbon Dioxide (CO2) Removal: Amine Gas Sweetening Process

One of the most established methods for CO2 removal from natural gas is **Amine Gas Sweetening**. The process involves the use of aqueous solutions of alkanolamines (such as monoethanolamine (MEA), diethanolamine (DEA), or methyldiethanolamine (MDEA)) to selectively absorb CO2 from the gas stream.

Process Flow:

Absorption Stage:

- The raw natural gas is passed through an absorber column where it comes into contact with the amine solution.
- CO2 is absorbed by the amine, forming a weak chemical bond. In this stage, most of the CO2 is removed from the gas, leaving behind purified natural gas.

Regeneration Stage:

- The CO2-rich amine solution is then sent to a regenerator where it is heated. The heat breaks the chemical bond between the CO2 and the amine, releasing the CO2 as a separate gas stream.
- The regenerated amine is recycled back into the absorption process, while the CO2 is captured for sequestration or vented (depending on regulations).

Technical Considerations:

- **Amine Selection**: MEA is effective for high CO2 concentrations but requires more energy to regenerate, while MDEA is preferred for lower CO2 concentrations and has lower regeneration costs.
- **Corrosion Control**: The presence of CO2 and water can cause corrosion in amine plants, so corrosion inhibitors are often added, and stainless-steel equipment is used in key areas.

Applications:

- The **Sleipner Gas Field** in Norway is a prominent example where CO2 is removed from natural gas using amine sweetening, and the captured CO2 is stored in subsea formations as part of a carbon capture and storage (CCS) initiative. This project has sequestered over 16 million tons of CO_2 since 1996.

b) Nitrogen (N_2) Removal: Cryogenic Distillation

Cryogenic distillation is the most efficient process for separating nitrogen from natural gas. This method takes advantage of the differing boiling points of nitrogen (-195.8°C) and methane (-161.5°C), allowing the two gases to be separated under very low temperatures.

Process Flow:

- **Pre-Cooling**: Natural gas is first cooled to a cryogenic temperature, causing the nitrogen to remain in a gaseous state while methane liquefies.
- **Distillation**: The liquefied methane is separated in a cryogenic distillation tower, where further separation occurs based on the vapor-liquid equilibrium. Nitrogen is vented or compressed for industrial uses, while methane (the primary component of natural gas) is retained as a liquid or gas for transport.

Technical Considerations:

- **Energy Consumption**: Cryogenic processes require significant energy input to achieve the low temperatures needed. However, the process produces high-purity methane and effectively removes nitrogen.
- **Operation Complexity**: Maintaining the precise temperature control needed for cryogenic distillation can be challenging, and any fluctuations can impact the purity of the gas.

Applications:

- Cryogenic distillation is used in facilities such as the **ExxonMobil LaBarge Plant** in Wyoming, which processes natural gas streams containing high levels of nitrogen. The purified methane is transported for commercial use, while nitrogen is often used in enhanced oil recovery (EOR) operations.

4) Water Vapor Removal: Glycol Dehydration

Glycol Dehydration is the industry standard for removing water vapor from natural gas. Water vapor must be removed to prevent hydrate formation, which can cause blockages in pipelines, and to avoid corrosion.

Process Flow:

- **Absorption**: Wet natural gas is fed into a contactor column, where it flows counter current to glycol (commonly triethylene glycol, TEG). The glycol absorbs water vapor from the gas stream, leaving the gas dry.
- **Regeneration**: The glycol, now rich in water, is sent to a regeneration unit where it is heated to remove the water and prepare the glycol for reuse.

Technical Considerations:

- **TEG Performance**: TEG is chosen because of its high affinity for water and its ability to be regenerated repeatedly. However, the energy required for regeneration can be significant, particularly in large-scale operations.
- **Energy Efficiency**: Some dehydration systems integrate heat recovery units to capture waste heat from the regeneration process, reducing overall energy consumption.

Applications:

- **Permian Basin** in the United States uses glycol dehydration extensively. As water vapor levels are high in the raw gas produced in this region, glycol dehydration helps ensure that the gas meets pipeline specifications, preventing hydrate formation and corrosion.

5) Heavy Hydrocarbons Removal: Joule-Thomson (JT) Expansion and Refrigeration

Heavy hydrocarbons (C5+ hydrocarbons) can condense and cause issues in pipelines, especially when natural gas is subjected to high pressures. **Joule-Thomson (JT) Expansion** and **Mechanical Refrigeration** are two common methods used to condense and remove these heavier molecules.

JT Expansion Process Flow:

- **Expansion Valve**: Natural gas is expanded rapidly through a JT valve, causing a significant drop in temperature. This cooling effect condenses heavy hydrocarbons (pentane, hexane, etc.), which are then separated from the gas stream.
- **Hydrocarbon Separation**: The condensed hydrocarbons are collected as a liquid phase, while the purified gas stream continues on for further processing or distribution.

Refrigeration Process Flow:

- **Cooling**: In mechanical refrigeration, the natural gas is cooled to a predetermined temperature using refrigeration cycles. This cooling causes heavy hydrocarbons to condense, and the liquid hydrocarbons are separated in a three-phase separator.

Technical Considerations:

- **Energy Losses in JT Expansion**: While JT expansion is simple and effective, it also results in a pressure loss. To counteract this, compression stages may be required downstream.
- **Refrigeration Complexity**: Mechanical refrigeration provides precise temperature control but requires continuous energy input for the refrigeration process.

Applications:

- JT expansion is widely used in the **Marcellus Shale** gas processing facilities, where natural gas liquids (NGLs) are extracted for sale, adding economic value. Heavy hydrocarbons are separated and sold as by-products, while purified gas is transported through pipelines.

6) Results and Impact of Natural Gas Purification

Natural gas purification, using the technologies discussed, ensures that the final product meets stringent pipeline and market specifications. This has several benefits:

- **Improved Energy Efficiency**: Removal of nitrogen, CO_2, and heavy hydrocarbons increases the calorific value of the gas, making it more efficient as a fuel.
- **Pipeline Safety**: The removal of corrosive compounds such as CO_2 and water vapor prevents pipeline corrosion and reduces the risk of blockages due to hydrate formation.

- **Environmental Benefits**: By capturing CO_2 during the purification process, gas processing facilities can significantly reduce greenhouse gas emissions, contributing to a lower carbon footprint. Some facilities, such as the **Sleipner project**, inject captured CO_2 into underground reservoirs for long-term storage.
- **Commercial Viability**: Purified natural gas is suitable for long-distance transportation in pipelines and LNG (Liquefied Natural Gas) systems, increasing its market value. By removing heavy hydrocarbons, NGLs can be sold as valuable by-products, improving the economics of gas processing.

7) Conclusion

Natural gas purification is a vital process that ensures the quality, safety, and marketability of natural gas. Through the removal of contaminants such as CO_2, nitrogen, water vapor, and heavy hydrocarbons, purification technologies help enhance the energy efficiency of the gas, prevent operational issues, and reduce environmental impacts.

Key technologies like amine gas sweetening, cryogenic distillation, glycol dehydration, and JT expansion offer efficient solutions for large-scale natural gas processing facilities. By employing these techniques, the natural gas industry not only meets commercial and regulatory standards but also plays a role in reducing the environmental footprint of gas production and transportation.

This case study highlights the importance of continued innovation and optimization in natural gas purification technologies to meet the evolving energy needs of the world while addressing sustainability challenges.

7. Case Study: Liquefaction of Natural Gas at the Wellhead – Costs and Viability

1) Introduction

Natural gas is a critical energy resource used in various sectors, including power generation, industrial processes, and transportation. However, transporting natural gas from the point of extraction (wellhead) to end users is a challenge, particularly for remote and offshore gas fields. One of the most effective ways to transport natural gas over long distances is by converting it into **Liquefied Natural Gas (LNG)**. The liquefaction process reduces the volume of natural gas by approximately 600 times, making it easier and more economical to transport in cryogenic tankers.

Liquefaction of natural gas can occur at various stages in the supply chain, including at centralized plants or at the wellhead. This case study focuses on the **liquefaction of natural gas at the wellhead**, evaluating its technical processes, costs, and overall viability. It explores the benefits and challenges associated with wellhead liquefaction, as well as real-world applications that highlight the potential of this approach.

2) Problem Definition: The Need for Wellhead Liquefaction

Natural gas extraction often occurs in remote locations, such as offshore platforms or isolated land-based fields, far from existing pipeline infrastructure. In these scenarios, traditional transportation methods (e.g., pipelines) are often unfeasible due to high costs, environmental concerns, or geographical barriers. Some key challenges include:

a) **Remote and Offshore Gas Fields**: Transporting natural gas from isolated fields to markets using pipelines requires significant capital investment and long development timelines. This makes traditional pipelines uneconomical for small to medium-sized fields or deep-water offshore reserves.
b) **Stranded Gas Reserves**: Many natural gas reserves remain "stranded" due to the absence of nearby infrastructure. Without viable transport options, these reserves cannot be developed and contribute to the global energy market.
c) **Transportation Over Long Distances**: Even when pipeline infrastructure is present, transporting natural gas over vast distances (especially over oceans) is inefficient, and liquefaction becomes the most feasible option.
d) **Global Demand for LNG**: As LNG becomes an increasingly important part of the global energy mix, especially in Asia and Europe, there is a growing need for technologies that can facilitate the liquefaction of natural gas at the source (wellhead), thus minimizing transportation costs and enabling export.

3) The Process of Liquefaction of Natural Gas at the Wellhead

a) Overview of Natural Gas Liquefaction

Liquefaction involves cooling natural gas to extremely low temperatures (around -162°C or -260°F), causing it to transition from a gaseous to a liquid state. In its liquid form, natural gas occupies about 1/600th of its gaseous volume, making it much easier to store and transport. The key steps involved in the liquefaction process are:

Pre-treatment:

- Before liquefaction, natural gas must be purified by removing impurities such as water vapor, carbon dioxide (CO_2), hydrogen sulphide (H_2S), and heavy hydrocarbons. These impurities could freeze during liquefaction, causing blockages or equipment damage.

Cooling and Liquefaction:

- The purified gas is then cooled using a series of refrigeration cycles, typically involving cryogenic processes like the **Joule-Thomson effect** or the use of refrigerants such as nitrogen or mixed refrigerants. The natural gas is cooled to -162°C, at which point it becomes a liquid (LNG).

Storage and Transportation:

- Once liquefied, LNG is stored in cryogenic tanks, usually at or near the wellhead in small-scale facilities, before being transported via specially designed LNG tankers or trucks to its destination (such as regasification terminals or direct consumers).

b) Wellhead Liquefaction Technologies

Wellhead liquefaction is generally implemented using **small-scale liquefaction units** that are modular and can be rapidly deployed. The most commonly used technologies include:

Paper ID: SR241006134022 DOI: https://dx.doi.org/10.21275/SR241006134022

- **Mixed Refrigerant Process**: This method uses a combination of refrigerants (such as nitrogen, methane, and ethane) to cool the gas to its liquefaction point. The mixed refrigerant process is compact and highly efficient, making it suitable for remote wellhead applications.
- **Joule-Thomson (JT) Expansion**: In JT expansion, natural gas is compressed and then expanded through a valve, causing a temperature drop and resulting in partial liquefaction. This method is relatively simple but less energy-efficient than other cryogenic technologies.
- **Turboexpander**: Turboexpander technology involves cooling the natural gas by expanding it through a turbine, which generates mechanical power that can be used to drive other processes. This method is more energy-efficient than JT expansion and is well-suited for small- to medium-scale liquefaction at the wellhead.
- **Nitrogen Expansion**: This process uses nitrogen as a refrigerant to cool and liquefy the natural gas. It is favoured for small-scale applications due to its simplicity and reliability.

c) Costs of Wellhead Liquefaction

The costs associated with wellhead liquefaction are determined by several factors, including the size of the field, the technology employed, and the distance to market. Below is a breakdown of the major cost components:

Capital Expenditures (Cap-Ex)

○ **Liquefaction Plant**:
- Building a small-scale liquefaction plant at the wellhead typically involves capital costs ranging from $500 to $1,200 per ton of LNG produced. This is significantly lower than the costs associated with large-scale liquefaction plants, which can exceed $2,000 per ton.
- Modular, pre-fabricated liquefaction units are often used at wellheads, which reduces the installation time and associated costs.

○ **Storage Tanks**:
- Cryogenic storage tanks for LNG can be a significant capital investment. The cost of small-scale cryogenic tanks ranges from $50,000 to $200,000, depending on capacity and the materials used.

Infrastructure Development:
- For remote wellheads, additional infrastructure (such as roads, power supply, and export facilities) may be required. The cost of this infrastructure depends on the location, with offshore facilities being considerably more expensive to develop than onshore fields.

d) Operational Expenditures (Op-Ex)

○ **Energy Consumption**:
- The energy required for liquefaction is one of the primary operating costs. Small-scale liquefaction units typically consume around 1.5 to 2.0 MMBtu (Million British Thermal Units) of energy for every ton of LNG produced.
- On an annual basis, energy costs can range from $20 to $50 per ton of LNG, depending on the efficiency of the liquefaction technology and the local energy price.

○ **Maintenance**:
- Maintaining cryogenic equipment in remote environments can be challenging and costly. Maintenance costs for small-scale liquefaction units are typically around 3-5% of the initial capital cost per year.
- Offshore installations incur higher maintenance costs due to the harsh operating environment, while onshore facilities can benefit from lower costs and easier access to parts and labour.

e) Transportation Costs

○ **LNG Transport**:
- Once liquefied, natural gas must be transported to market. For remote or offshore fields, LNG is typically transported by specialized LNG tankers. The cost of transporting LNG depends on the distance to the destination, with longer distances leading to higher shipping costs.
- On average, transportation costs for LNG are estimated to be around $0.5 to $1.5 per MMBtu, though this varies based on the scale of the operation and the distance to market.

8. Viability of Wellhead Liquefaction

8.1 Economic Viability

Wellhead liquefaction is economically viable in specific scenarios, particularly for remote and offshore fields where traditional pipelines are prohibitively expensive or technically unfeasible. The following factors contribute to the economic feasibility of wellhead liquefaction:

- **Stranded Gas Reserves**: Fields that are located far from existing infrastructure or in deep offshore environments can benefit from wellhead liquefaction. By converting natural gas to LNG at the source, operators can monetize previously stranded gas reserves.
- **Lower Upfront Investment**: Compared to large-scale centralized liquefaction facilities, wellhead liquefaction units have a lower initial capital cost. Modular units can be deployed relatively quickly, allowing for earlier cash flow from LNG exports.
- **Scalability**: Wellhead liquefaction facilities can be easily scaled based on the size of the field. This makes it an attractive option for small- to medium-sized fields, which may not justify the construction of large infrastructure.
- **Favourable LNG Market**: The global LNG market has grown significantly, driven by demand from countries like China, Japan, and South Korea. By exporting LNG directly from the wellhead, producers can take advantage of higher prices in global markets compared to local natural gas prices.

8.2 Technological Viability

- **Modularization**: Advances in liquefaction technology have enabled the development of modular liquefaction units that can be quickly deployed at wellheads. These units are compact, pre-fabricated, and can be easily transported to remote locations. Their modular nature allows for flexible capacity increases as production scales.

- **Energy Efficiency**: Modern small-scale liquefaction technologies, such as mixed refrigerant and turboexpander processes, offer higher energy efficiency compared to traditional methods like JT expansion. These technologies reduce operating costs and improve overall profitability.
- **Logistics and Infrastructure**: For offshore gas fields, floating LNG (FLNG) solutions are becoming more prevalent. FLNG units are essentially floating liquefaction plants that process and liquefy natural gas directly on-site, eliminating the need for pipelines and land-based infrastructure.

8.3 Environmental and Regulatory Considerations

- **Environmental Impact**: The liquefaction process requires significant energy and results in emissions of CO2 and other pollutants. However, wellhead liquefaction can reduce the overall environmental impact by eliminating the need for long-distance pipelines, which often involve land disturbance and ecosystem disruption.
- **Carbon Capture and Storage (CCS)**: Some wellhead liquefaction facilities are being designed with integrated CCS technology, where CO2 is captured during pre-treatment and stored in underground formations. This reduces the carbon footprint of the liquefaction process and can help meet increasingly stringent environmental regulations.
- **Regulatory Compliance**: LNG exports are subject to stringent regulations, particularly concerning safety, emissions, and environmental impact. Wellhead liquefaction projects must comply with these regulations, which can increase costs and require additional investment in monitoring and compliance systems.

8.4 Conclusion

Wellhead liquefaction presents a viable solution for monetizing remote and stranded natural gas reserves, particularly in areas where traditional pipeline infrastructure is not economically feasible. By liquefying natural gas at the wellhead, operators can reduce transportation costs, improve energy efficiency, and tap into the growing global LNG market.

The economic viability of wellhead liquefaction depends on several factors, including the size of the gas field, the technology employed, and the distance to market. While the capital and operating costs of small-scale liquefaction units are lower than large-scale facilities, challenges such as high energy consumption, regulatory compliance, and maintenance in remote environments must be addressed.

9. Challenges and Limitations

9.1 Technological Barriers

Despite advancements in refuelling technologies, several technical challenges remain that hinder widespread adoption and optimization. Hydrogen refuelling infrastructure, for example, requires specialized equipment, including high-pressure storage tanks and compressors, which are expensive to install and maintain. Additionally, hydrogen's low energy density compared to conventional fuels means that more frequent refuelling is necessary, limiting its range in some applications.

Similarly, for LNG and biogas refuelling systems, the primary challenge lies in fuel handling and storage. Methane, the primary component of both LNG and biogas, is a highly potent greenhouse gas, and any leaks during storage or transfer can negate the environmental benefits of switching to these fuels. Developing more reliable leak detection and prevention systems is essential to addressing this challenge.

9.2 Economic Challenges

The economic viability of optimized gas refuelling solutions varies depending on the region, fuel type, and scale of the infrastructure. Hydrogen refuelling stations, for instance, have a high initial capital cost, often requiring substantial government subsidies or private investments to become commercially viable. Even with technological innovations that reduce operational costs, the return on investment (ROI) can take years, making it less attractive to investors.

Biogas refuelling faces similar economic challenges in regions with undeveloped infrastructure. Although the technology is relatively simple, it requires a consistent source of organic waste and local expertise for operation and maintenance. In remote areas, this can increase costs, making it harder for projects to be self-sustaining without external financial support.

9.3 Public Perception and Adoption

A major barrier to the optimization of refuelling systems is public perception. Hydrogen, in particular, suffers from safety concerns due to its high flammability, even though modern safety systems mitigate these risks. Public awareness campaigns are necessary to educate consumers on the benefits and safety of alternative fuels, such as hydrogen and biogas, to encourage widespread adoption.

Additionally, the slow transition from gasoline and diesel vehicles to those powered by LNG, hydrogen, or biogas presents a limitation. The cost and availability of refuelling infrastructure must align with consumer demand, and a lack of refuelling stations could deter potential buyers from switching to cleaner fuel options.

10. Future Directions and Recommendations

10.1 Research Priorities

To advance the optimization of gas refuelling systems, focused research is needed in several key areas:

- **Cost Reduction in Hydrogen Refuelling Systems**: Hydrogen infrastructure requires substantial capital investment, particularly in terms of pressurized storage tanks, fuel dispensers, and energy-efficient compressors. Research into reducing the cost of hydrogen production through renewable energy sources, such as electrolysis powered by solar or wind, is crucial to making hydrogen a commercially viable option on a global scale.

- **Leak Prevention and Detection**: Methane leaks remain a significant challenge for LNG and biogas refuelling systems, compromising their environmental benefits. Advances in real-time leak detection systems and better tank materials (such as graphene-enhanced composites) could reduce methane emissions and improve the environmental performance of these alternative fuels.
- **Improved Fuel Storage Technologies**: Research into developing lightweight, corrosion-resistant materials for fuel storage tanks is necessary. Innovations in nanotechnology and advanced polymers could help extend the lifecycle of storage systems and reduce energy consumption during transportation and storage.

10.2 Technological Advancements

Future refuelling systems must integrate emerging technologies to optimize their performance:

- **AI and Predictive Analytics**: Ongoing advancements in AI, big data, and machine learning will allow fuel companies to more accurately forecast demand, reduce fuel losses, and optimize delivery schedules. These technologies will play a pivotal role in the next generation of refuelling systems, ensuring that fuel is delivered when and where it is needed, with minimal environmental impact.
- **Hybrid Refuelling Systems**: The future of gas refuelling may involve hybrid systems that integrate traditional fuels with renewable energy sources. For example, refuelling stations powered by solar or wind energy could use energy recovery systems to capture excess electricity, thereby enhancing overall sustainability.

10.3 Policy and Collaboration

Governments need to provide stronger policy frameworks to incentivize the adoption of optimized refuelling technologies:

- **Stronger Incentives for Alternative Fuels**: Financial incentives, such as subsidies for hydrogen and biogas refuelling stations, tax credits for fleet operators using alternative fuels, and carbon credits for reducing emissions, will accelerate the transition to optimized systems.
- **International Collaboration on Standards**: Countries must work together to develop international standards for hydrogen and alternative fuel refuelling infrastructure. Standardization will ensure compatibility between systems across borders, allowing for greater scalability and adoption.

10.4 Integration with Renewable Energy

The coupling of renewable energy sources, such as solar and wind, with gas refuelling systems can further reduce carbon emissions. For example, electrolysis powered by solar energy to produce hydrogen on-site at refuelling stations would make the process far more sustainable. This hybrid approach reduces reliance on centralized fuel production and opens the door to decentralized, off-grid refuelling solutions.

11. Conclusion

The optimization of gas refuelling systems is critical to achieving a sustainable energy future. As the world continues to shift toward reducing carbon emissions and minimizing environmental impacts, traditional fossil fuel-based refuelling infrastructure must evolve to meet these global goals. This paper has explored various optimization strategies, including technological innovations, data-driven management, and policy frameworks, all of which play essential roles in making gas refuelling systems more efficient and sustainable.

Emerging technologies, such as AI and IoT, offer promising avenues for improving fuel delivery logistics, minimizing fuel losses, and optimizing fuel demand forecasting. Additionally, advances in materials science, including the development of composite storage tanks and nanotechnology-based leak prevention systems, can significantly enhance the environmental performance of refuelling infrastructure. Hydrogen and biogas, in particular, hold great potential as alternative fuels, but their infrastructure must be optimized for widespread adoption.

The case studies presented in this paper demonstrate real-world applications of optimized refuelling systems, showing the potential for reduced emissions, cost savings, and improved operational efficiency. However, significant challenges remain, particularly in terms of technological and economic barriers, public perception, and the slow transition from traditional fuels to cleaner alternatives.

Looking forward, collaboration between governments, industries, and research institutions will be essential in driving the transition to sustainable refuelling systems. Stronger policy incentives, international collaboration on standards, and further research into cost reduction and efficiency improvements are critical to ensuring that optimized refuelling solutions can support global energy needs while minimizing their environmental impact.

In conclusion, optimizing gas refuelling systems is not just a technological challenge but also a policy and societal one. The future of refuelling must be rooted in sustainability, and with continued innovation and collaboration, the global community can make substantial strides toward achieving this goal.

As demand for LNG continues to grow, particularly in Asia and Europe, wellhead liquefaction offers a flexible and scalable solution for unlocking the potential of natural gas resources worldwide. With continued advancements in liquefaction technology and the increasing availability of modular units, wellhead liquefaction is likely to play an increasingly important role in the future of the natural gas industry.

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