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COMPARATIVE ANALYSIS OF HYDROGEN SYNTHESIS TECHNOLOGIES FROM METHANE FEEDSTOCK

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Abstract

This article provides a comparative analysis of the primary technologies for hydrogen synthesis from methane feedstock: steam methane reforming (SMR), partial oxidation (POX), autothermal reforming (ATR), and dry reforming (DR). The techno-economic indicators, energy efficiency, carbon footprint, and industrial application potential of each technology are examined. The prospects for integration with Carbon Capture and Storage (CCS/CCUS) technologies, which have developed rapidly in recent years, and the concept of "Blue hydrogen" are discussed. The literature review indicates that SMR remains the most widespread and economically efficient method; however, ATR and dry reforming technologies are emerging as serious competitors in terms of environmental sustainability.

Index Terms

Hydrogen production, methane reforming, steam methane reforming (SMR), partial oxidation (POX), autothermal reforming (ATR), dry reforming, blue hydrogen, CCS/CCUS, energy efficiency.

I. INTRODUCTION

The global energy paradigm is currently undergoing a fundamental shift towards decarbonization, where hydrogen (H_2) emerges as a pivotal energy carrier for a sustainable future. According to the International Energy Agency (IEA), global hydrogen demand is projected to escalate to 150 million tonnes by 2030, driven by the decarbonization of heavy industries and the transport sector [1], [2]. Despite the rapid growth of water electrolysis, over 95% of the world's hydrogen is still synthesized from hydrocarbon feedstocks, predominantly methane [3]. Methane-based sources-ranging from conventional natural gas to biogas and shale gas-remain the most economically viable and technically mature precursors. The chemical architecture of the methane molecule (CH_4), characterized by a high hydrogen-to-carbon ratio and 25% hydrogen content by mass, positions it as an unparalleled feedstock for large-scale industrial applications [4], [5].

However, the transition to a low-carbon economy necessitates a critical re-evaluation of existing methane conversion pathways. While Steam Methane Reforming (SMR) has historically dominated the market, its high carbon intensity poses significant environmental challenges. Alternative thermochemical processes, such as Partial Oxidation (POX), Autothermal Reforming (ATR), and Dry Reforming (DR), offer distinct operational advantages, ranging from superior thermal efficiency to the utilization of as a co-reactant. The selection of an optimal reforming technology is a multi-dimensional optimization problem, involving complex trade-offs between specific energy consumption, Capital Expenditure (CAPEX), and life-cycle greenhouse gas emissions [6], [7].

Despite the extensive body of literature on individual reforming techniques, there is a conspicuous lack of recent, comprehensive reviews that provide a synchronized comparative analysis of SMR, POX, ATR, and DR within a unified technical and economic framework. Furthermore, the integration of these technologies with Carbon Capture, Utilization, and Storage (CCUS) is becoming a prerequisite for "Blue Hydrogen" production. This paper aims to bridge this knowledge gap by conducting a rigorous comparative evaluation of these four technologies. By synthesizing technical performance metrics, economic feasibility, and environmental footprints, this review provides a strategic roadmap for selecting the most sustainable hydrogen production pathways in the context of modern climate targets.

II. METHODOLOGY

A. General approach

Steam Methane Reforming SMR is currently the most widely used industrial technology for hydrogen production. The process occurs in two stages: in the first stage, methane reacts with steam at high temperatures (700-900 °C); in the second stage, the Water-Gas Shift (WGS) reaction is performed [4-5]:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \quad \Delta H = +206 \text{ kJ/mol} \tag{1}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H = -41 \text{ kJ/mol} \tag{2}$$

Ni-based catalysts are used in the SMR process, and pressure is typically maintained between 15-40 bar. The primary advantages of this technology are relatively low capital costs and high hydrogen yield (80-85% efficiency from methane) [6-7]. Modern SMR units can reach capacities of 100,000–300,000 Nm^3 H_2 per day. The main disadvantage is the emission of approximately 9-12 kg of CO_2 for every 1 kg of H_2 produced, representing a high environmental footprint [8].

B. Model structure

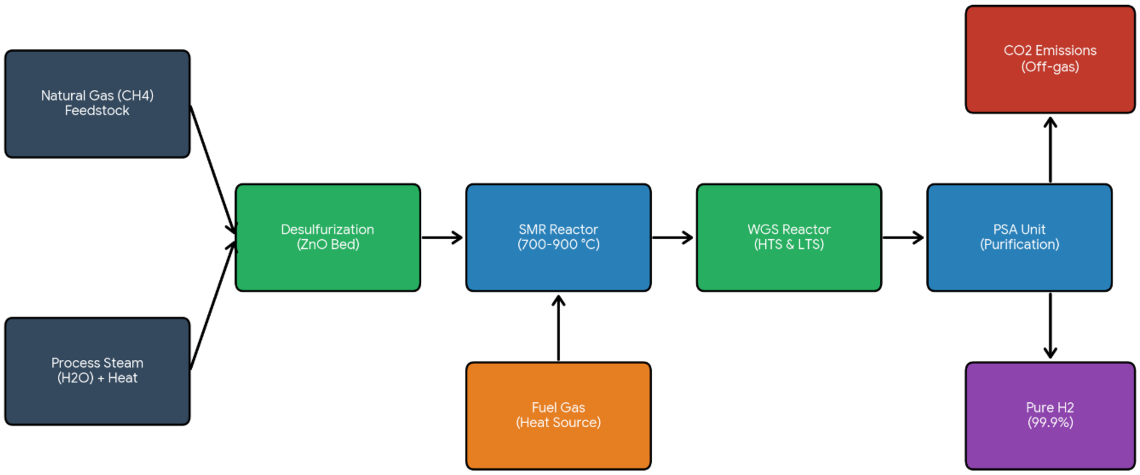

Fig. 1. Technological block diagram of the Steam Methane Reforming (SMR) process

Major manufacturers-Air Products, Linde, and Haldor Topsoe are continuously improving SMR technology. By introducing membrane reactors and heat recuperation systems, overall efficiency is being increased by 1-3% [9-10]. Recycling 80-85% of the thermal energy generated in the unit has now become standard practice.

In the partial oxidation process, methane reacts with a limited amount of oxygen. The process is exothermic, meaning no external heat source is required [8]:

$$CH_4 + \tfrac{1}{2}O_2 \rightarrow CO + 2H_2 \quad \Delta H = -36 \text{ kJ/mol} \tag{3}$$

Non-catalytic POX is conducted at temperatures of 1300-1500 °C, while the catalytic version operates at 800–1000 °C. The primary strength of this technology is its rapid startup capability and the relative compactness of the equipment. These features allow POX to be used in mobile and distributed energy systems [9, 11-12]. However, the additional capital expenditure required for Air Separation Units (ASU) to produce pure oxygen has historically limited the widespread adoption of POX.

C. Autothermal Reforming (ATR)

ATR represents a combination of SMR and POX technologies. Inside the reactor, steam-methane reforming and partial oxidation occur simultaneously, resulting in a self-sustaining heat balance [10]:

$$4CH_4 + 2H_2O + O_2 \rightarrow 4CO + 10H_2 \quad (\Delta H \approx 0) \tag{4}$$

A significant advantage of ATR is the ability to operatively manage the H_2/CO ratio. This feature is particularly valuable for downstream processes such as Fischer-Tropsch synthesis and methanol production. Companies like Shell and Haldor Topsoe have successfully implemented ATR technology in large-scale Gas-to-Liquids (GTL) projects [14-15]. ATR is also more easily integrated with CCS systems because the concentration of CO_2 in the exit gas is higher.

III. RESULTS AND DISCUSSION

A. General observations

In dry reforming technology, methane reacts with CO_2 instead of steam. This process allows for the simultaneous utilization of two greenhouse gases—CH_4 and CO_2 [12]:

$$CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2 \ (\Delta H = +247 \text{ kJ/mol}) \tag{5}$$

Although dry reforming is attractive from an environmental standpoint, several technical challenges-such as catalyst deactivation due to coke deposition and high energy consumption-limit its broad industrial application. Research into Ni-Co bi-component and Rh/Ru-based catalysts is showing high success in increasing resistance to coke formation [13]. Several pilot plants are currently operational, and optimization work is ongoing for industrial-scale implementation.

B. Comparative analysis of technologies

The following main criteria are considered when comparing the technologies: hydrogen yield, energy consumption, CO_2 emissions, capital and operational costs, and Technology Readiness Level (TRL).

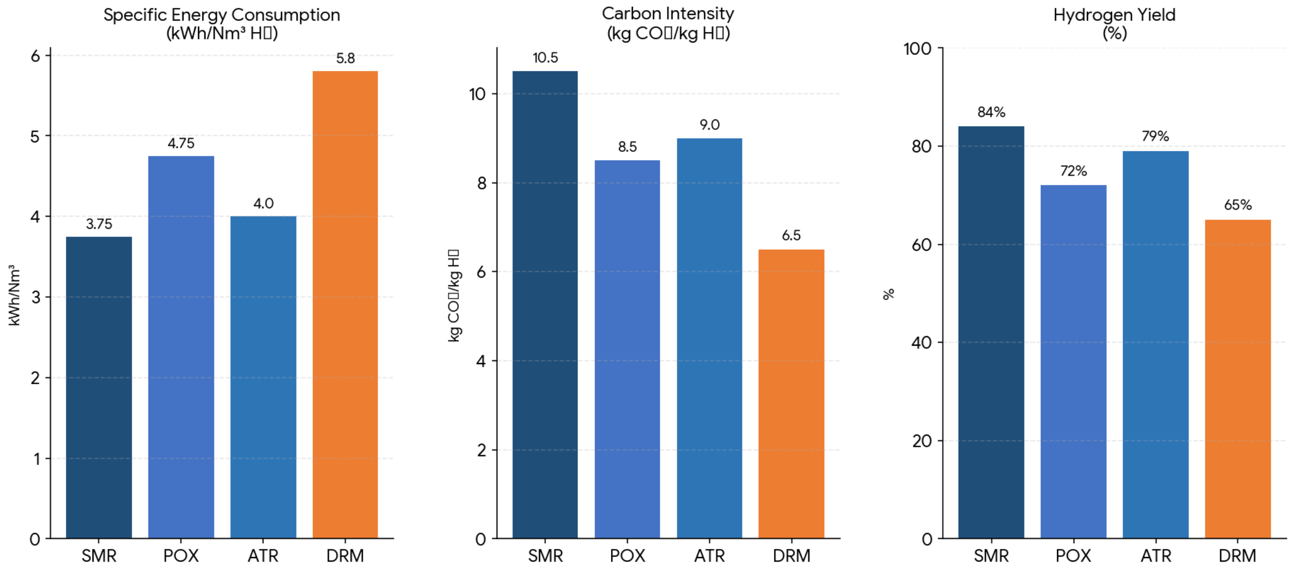

Fig. 2. Key technical indicators of methane reforming technologies
(energy consumption, CO_2 emissions, hydrogen yield)

C. Energy efficiency

In terms of energy efficiency, SMR exhibits the highest performance, consuming 3.5-4.0 kWh per 1 Nm^3 of H_2. The POX technology requires 4.5-5.0 kWh/Nm^3, while ATR falls in the 3.8-4.2 kWh/Nm^3 range, remaining competitive at the system level when equipment compactness is considered [14]. As shown in Figure 2 above, SMR leads in hydrogen yield (84%), while dry reforming (65%) still requires optimization.

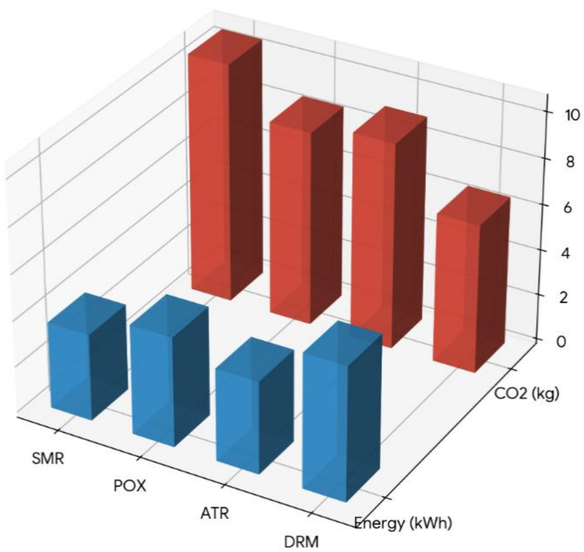

Fig. 3. Comparative 3D Analysis of Energy Consumption and Carbon Intensity for Methane Reforming Technologies

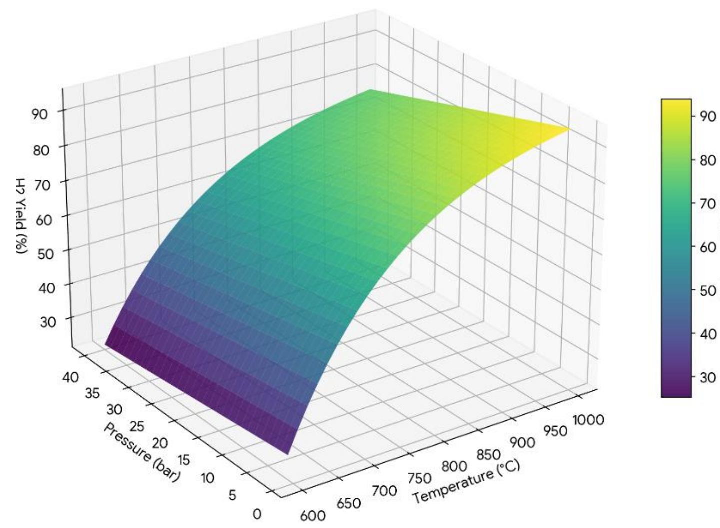

Fig. 4. 3D surface plot representing the thermodynamic efficiency of methane reforming as a function of temperature and pressure

Fig. 3. Comparative 3D analysis of energy intensity and carbon emissions across four methane reforming technologies. While SMR exhibits the highest energy efficiency, it remains the most carbon-intensive process; conversely, DRM minimizes CO_2 emissions but requires the highest specific energy input.

The (Fig. 4.) visualization demonstrates the significant impact of operating conditions on hydrogen yield. An increase in temperature from 600°C to 1000°C drastically enhances the conversion rate due to the endothermic nature of the reaction, while higher pressure slightly suppresses the yield according to Le Chatelier's principle.

According to cost analysis, at current gas prices, the production cost of H_2 using SMR is $1.0 - $2.5 USD (without CCS). For "blue hydrogen" with CCS, this figure rises to $1.5-$3.5 USD [15]. Although POX and ATR technologies have 15-25% higher capital costs than SMR, their total life-cycle costs can equalize in certain industrial segments due to operational savings.

The best results for CO_2 emissions were recorded in ATR technology combined with CCS; by ensuring 90 - 95% CO_2 capture from the processed gas stream, net emissions can be reduced to 1 - 2 kg CO_2/kg H_2. Dry reforming could potentially be net-neutral or even negative, but this is only achievable if the energy supply source is renewable.

D. Blue Hydrogen and Carbon Capture

The concept of “Blue hydrogen” is built on combining methane reforming with Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCUS). Between post-combustion and pre-combustion capture strategies, the pre-combustion approach (capturing CO_2 after the water-gas shift reaction) is economically preferred for methane reforming because the CO_2 concentration in the capture stream is high (>40%) and the pressure is elevated [15].

Modern amine absorption technology (MEA, MDEA solutions) allows for up to 90% CO_2 capture, though regeneration energy (3-4 GJ/t CO_2) significantly increases operational costs. Membrane separation and cryogenic methods are attracting great interest as next-generation CCS technologies and are currently being tested at the pilot scale [16]. According to the IEA, SMR and ATR units equipped with CCS could provide more than 40% of global blue hydrogen production by 2030.

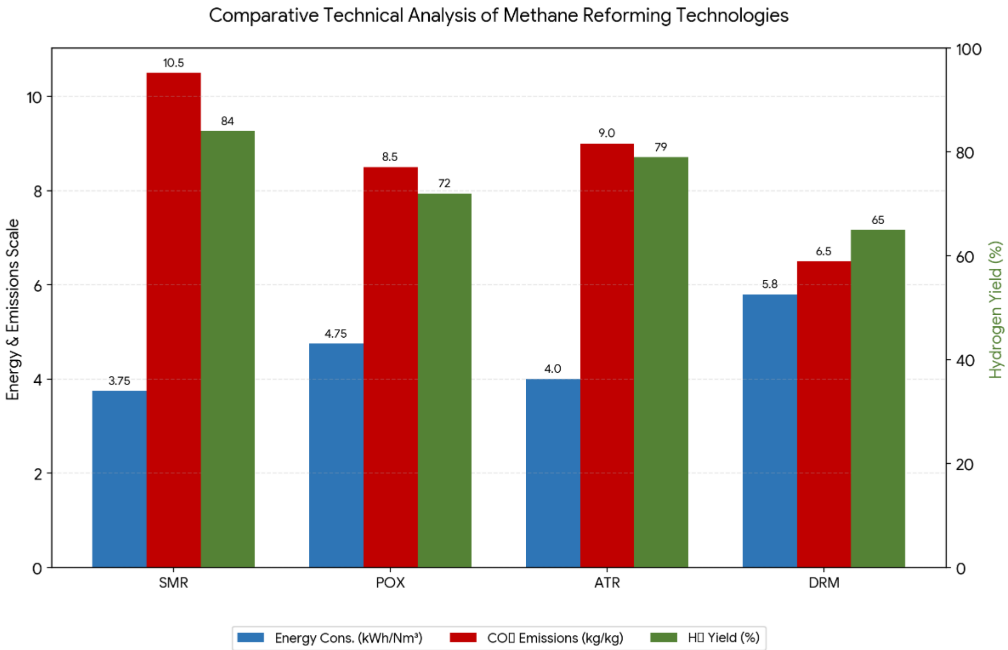

Fig. 5. Comparative technical performance of methane reforming technologies based on energy consumption, CO_2 emissions, and hydrogen yield

Fig. 5, presents a comprehensive technical assessment of methane reforming technologies by correlating energy consumption and carbon intensity with hydrogen yield. The data reveals that Steam Methane Reforming (SMR) achieves a peak hydrogen yield of 84%, established as the most productive pathway among the studied methods. However, SMR is simultaneously characterized by the highest carbon footprint, releasing 10.5 kg of CO_2 per kilogram of hydrogen produced. In stark contrast, Dry Reforming of Methane (DRM) demonstrates a superior environmental profile with the lowest emissions at 6.5 kg CO_2/kg H_2, primarily due to its utilization of carbon dioxide as a reactant. Despite its ecological advantages, DRM requires a significantly higher specific energy input of 5.8 kWh/Nm^3, highlighting a critical energy-emission trade-off. Ultimately, these results provide a quantitative basis for selecting the optimal synthesis technology based on specific industrial and environmental priorities.

E. Current Trends and Innovation

Literature analysis indicates that methane reforming technologies are rapidly developing in several key areas:

- Membrane Reactors: Based on Le Chatelier's principle, they ensure continuous hydrogen separation from the reaction zone, increasing conversion levels by 30-40% [14].
- New Technologies: Plasma catalysis and microwave-excited reactors are being actively researched to reduce energy consumption.
- Digitalization: The use of Artificial Intelligence (AI) and Machine Learning for real-time reactor mode optimization is being implemented in the industry.

IV. CONCLUSION

Global competition between “Blue hydrogen” and “Green hydrogen” is intensifying. Some forecasts suggest that as electrolysis costs decline, green hydrogen may reach price parity with blue hydrogen by 2035–2040 [15-18]. Therefore, research to reduce capital costs and improve CO_2 capture efficiency is continuing rapidly to maintain the competitiveness of methane reforming. In the context of

Uzbekistan, given the vast reserves of natural gas, SMR and ATR technologies could hold strategic importance for establishing a domestic hydrogen economy.

Based on the comparative literature review provided, the following conclusions can be drawn:

1. Steam Methane Reforming (SMR) technology currently holds the leading position in terms of technical maturity, economic efficiency, and industrial scale, and it is expected to maintain this status in the near term.
2. Autothermal Reforming (ATR) stands out as the most promising technology for integration with CCS/CCUS and within large-scale Gas-to-Liquids (GTL) complexes, forming the cornerstone of “Blue hydrogen” strategies.
3. Dry Reforming holds significant ecological and strategic importance in the context of combating climate change; however, it requires intensive research to improve catalyst stability and reduce energy consumption.
4. The full implementation of the “Blue hydrogen” concept depends on overcoming the technical and economic challenges of CCS technology integration, though this field currently remains one of the most actively invested areas globally.
5. Recommended directions for future research include: transitioning membrane reactors to industrial scales, developing next-generation catalysts, and conducting techno-economic feasibility studies to select optimal technologies specifically for the conditions of Uzbekistan

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