https://doi.org/10.33271/nvngu/2024-1/092

Duyen Quang Le[*1],
orcid.org/0000-0001-6953-4762,
Nguyen The Dzung[2],
orcid.org/0009-0000-4018-3583

1 – Faculty of Petroleum and Energy, Hanoi University of Mining and Geology, Hanoi, the Socialist Republic of Vietnam
2 – Petrography & Petrophics Department of Research & Engineering Institute, Join Venture Viet-Nga Vietsovpetro, Vung Tau, the Socialist Republic of Vietnam
[*] Corresponding author e-mail: lequangduyen@humg.edu.vn

AN OVERVIEW OF HYDROGEN PRODUCTION VIA REFORMING FROM NATURAL GAS

Purpose. To provide an extensive analysis of hydrogen production and the major benefits as well as challenges in the hydrogen production from natural gas.

Methodology. The systematic review approach was used in this study. The first stage in a holistic evaluation is to find related significant works and specific concepts, and then apply them to search phrases and syntax. A thorough search is implemented in the Web of Science, Google Scholar, Science Direct, and Scopus databases in the English language. Moreover, the publication time of the papers is also limited in the period from 2010 to September 2023.

Findings. The literature review revealed that natural gas reforming is the most prevalent technique for producing hydrogen. The obtained results also showed that the approach based on automatic thermal reforming is less common than the one that uses natural gas to create hydrogen by steam reforming. Additionally, natural gas steam reforming has the most harmful environmental influences with regard to abiotic degradation, potential global warming, and other influence types.

Originality. This analysis offers an in-depth overview of how hydrogen is produced from natural gas as well as the benefits and limitations of the reforming method for producing hydrogen.

Practical value. From the literature review, it was found that the current preferred method for creating hydrogen is steam natural gas reforming. In addition, this review provides a comprehensive and useful resource for study, scientific advancement, and advancement in the disciplines of creating hydrogen.

Keywords: *hydrogen production, natural gas, steam reforming, autothermal reforming*

Introduction. Hydrogen can be generated by a variety of domestic resources, including nuclear power and alternative energy sources like hydroelectric, geothermal, solar, and wind power to separate water, as well as fossil fuels like biomass manufactured from non-food, renewable plants or coal and natural gas, preferably with the capture, usage, and storage of carbon [1]. Literature shows that 48 % of hydrogen produced now comes from steam reforming natural gas (SR), 30 % from petroleum fractions, 18 % from coal-based gasification, and just 4 % from the process of electrolysis due to the relatively high cost of production [2]. According to [3], there are numerous methods to produce hydrogen including electrochemical, thermochemical, photochemical, photocatalytic, and photoelectrochemical processes. [4] suggested different hydrogen production processes such as pyrolysis, gasification, steam reforming of natural gas, dark fermentation, photobiolysis, water electrolysis, and renewable liquid reforming. Additionally, [5] identified that hydrogen may be generated from fossil fuels (or fuels-derived biomass and biomass) using a variety of methods, including partial oxidization, reforming by steam (mostly of gas that comes from nature), auto-thermal reforming, and coal gasification.

There are some reviews on various hydrogen production pathways. Since 2009, [6] have provided an overview of technologies associated with hydrogen generation, including renewable biomass resources that are both fossil and renewable. These technologies involve various methods such as reforming, and pyrolysis. [7] conducted a brief review of the most recent advancements in the extraction of hydrogen. With the view that using solar energy to produce hydrogen would be one of the most practical methods to substitute fossil-based production of hydrogen, [8] conducted a review of hydrogen manufacturing techniques using solar. From a safety perspective, [9] analyzed the techniques for manufacturing hydrogen. In addition to mentioning various production methods, [4] have conducted a techno-economic evaluation of numerous approaches. While [10] reviewed and assessed hydrogen production techniques for increased sustainability, [11] presented the current situation, difficulties, and possibilities for producing hydrogen, [12] mentioned the future developments of the technologies utilized for hydrogen generation. Besides, possibilities and obstacles in hydrogen production and use can be found in the study of [13]. Some other publications focus on specific methods for creating this production such as using biomasses, waste, renewable and non-renewable sources, geothermal energy, biomass, coal gasification, solar energy, gaseous fuels. Notably, some scientists have identified the potential of hydrogen production in their nations such as China, Mexico, Malaysia, Philippines, etc.

Since it is currently the most readily available resource for manufacturing on an industrial scale, natural gas is utilized as a frequent material [14]. Therefore, the usage of natural gas in the creation of hydrogen is also presented in some research. The cheapest method for supplying hydrogen is by far natural gas-derived hydrogen. Despite the existence of numerous hydrogen production techniques in various studies, there is no study that review the application of natural gas to create this product. This study analyzed thoroughly the production procedures and the major challenges in processing natural gas into hydrogen. In addition, this review provides a comprehensive and useful resource for research, scientific advancement, and advancement in the disciplines of creating hydrogen.

Methodology. The first stage in a holistic evaluation is to identify linked important works and particular concepts, and then apply them to find phrases and syntax. In this review, to facilitate research retrieval, they are arranged as follows: “hydrogen production”; “hydrogen generation”; “hydrogen creation”; “hydrogen production/generation methods”; “hydrogen production/generation from natural gas”. A thorough search is carried out in the Science Direct, Google Scholar, Web of Science, and Scopus databases in the English language. Table 1 provides a summary of the search syntaxes used for the study retrieval.

The titles, keywords, and abstracts of publications were examined to figure out if they match this review’s topic. Additionally, the publication time of the papers is also limited in the period from 2010 to September 2023. This limitation helps to reduce the number as well as choose the publications with the latest information, the most up-to-date used method and technology.

The collected research studies were screened based on their relevance to specific domain of this review. As shown in Fig. 1, the search process focused mainly on two approaches for hydrogen production including steam reforming and autothermal reforming of natural gas.

After removing duplicates, screening is done to verify eligibility requirements based on titles and abstracts. Next, the complete texts of the manuscripts were retrieved in order to incorporate them into the review. 12,568 articles were found using the keywords specified in Table 1. Due to issues with titles, abstracts, and duplicate removal screening, a total of 12,350 manuscripts were rejected. The applicability of the remaining 268 papers was evaluated for every application. Only 43 full-text publications that satisfied the previously indicated requirements were thus gathered for review.

Table 1

The search syntaxes

Hydrogen and related term	Natural gas and related terms
Hydrogen	Natural gas
Hydrogen creation	Auto-thermal reforming of natural gas
Hydrogen generation	Natural gas steam reforming
Hydrogen production	

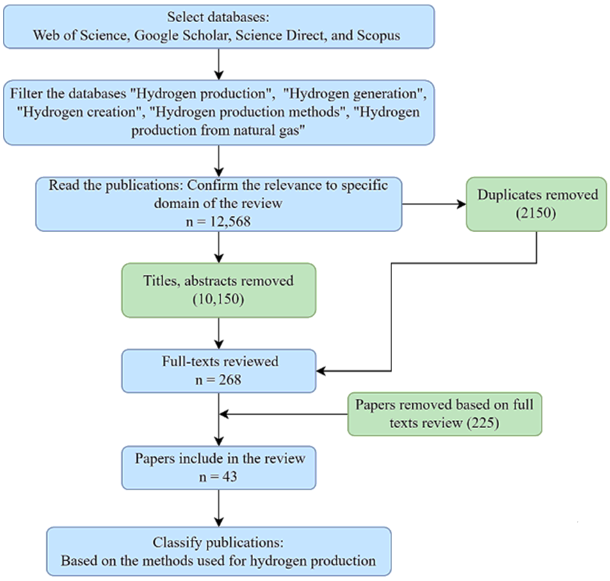

Fig. 1. Process of the literature search

Methods for producing hydrogen from natural gas. According to [15], in the periodic table of elements, hydrogen is the first chemical element. It ranks ninth in the crust of the Earth and is the most plentiful element in the universe. Atoms of hydrogen are mostly found in compounds. Thus, artificial manufacturing is required for hydrogen gas that can be used as an energy carrier. There are numerous methods and technologies that can be used to generate hydrogen. For utilizing natural gas as a material in producing hydrogen, all techniques need energy and feedstocks, such as renewable biomass and fossil fuels that are non-renewable, as well as other sources like wind, solar energy, etc. [15]. In order to create hydrogen from fossil fuels with zero or minimal impact on the environment, all of the carbon dioxide and other pollutants must be managed. The main energy sources for producing hydrogen include thermal, electrical, photonic, and biological energy [10]. The most favored process for creating hydrogen is natural gas reforming. The reforming reaction can be set up as partial oxidation ($O_2 + CH_4$), steam reforming ($H_2O + CH_4$), dry reforming ($CO_2 + CH_4$), or a combination of the foregoing [16]. Table 2 shows the reactant forms and features of these reactions [17]

Regarding the use of natural gas as a raw materials in generating hydrogen, [14] assessed and compared four technologies including auto-thermal reforming, steam methane reforming, and two novel techniques: chemical looping reforming and syngas chemical looping. In this study, the authors review and assess the following technologies of hydrogen generation using natural gas as feedstock.

Natural gas steam reforming for the generation of hydrogen. Steam reforming is a developed methodology for producing hydrogen utilizing nonrenewable feed stocks such as liquid petroleum gas (mainly butane and propane), methanol), jet fuel, naphtha, and diesel. Steam reforming of natural gas is an endothermic procedure that is more complex and demands high temperature source (from 700 to 1,000 °C) for operating [4]. The process of producing hydrogen using steam reforming of natural gas shows in the Fig. 2. In recent years, the most frequently utilized hydrogen generation is natural gas steam reforming and provides around 45 % of the products made with hydrogen [15]. Natural gas reforming includes an endothermic reaction at high temperatures between methane and steam based on the general procedure described below [18]

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2. \qquad (1)$$

Steam natural gas reforming has been proposed for a long time and is very well established but still subjected to perfection. According to [19], the procedure of regular natural gas steam reforming process essentially comprises these three steps:

- producing synthetic gases;
- undergoing the reaction of the water-gas shift;
- purifying the gas.

According to [20], the method of choice for producing hydrogen at the moment is steam natural gas reforming. The integration of steam reforming into concentrated solar systems with thermal storage enables uninterrupted hydrogen produc-

Table 2

Various reforming reactions

Reactant types	Reaction	Heat of reaction, kj/mol
Steam reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$	225.4
Dry reforming	$CH_4 + CO_2 \rightarrow 2CO + 2H_2$	260.5
Partial oxidation	$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	22.6

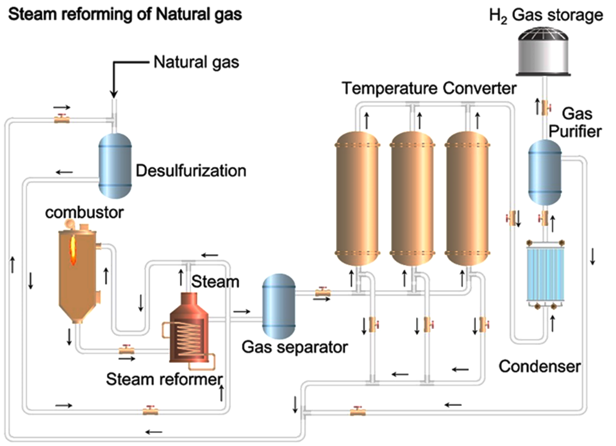

Fig. 2. The method for producing hydrogen by steam reforming natural gas [4]

tion. In particular, the cost of producing hydrogen could be significantly decreased both environmentally and economically thanks to this advancement. [20] reviewed improvements in natural gas reforming to produce hydrogen using concentrated solar energy and thermal energy storage. Fig. 3, *a* depicts the SMR with nickel present on a TiO_2 support, whereas Fig. 3, *b* shows a schematic of the entire process. While TiO_2 is a promoter to the most common alumina support, it is not a catalyst support.

Life cycle assessment of this method has been mentioned since the early *21st* century [20]. The thermal manufacturing process, which employs steam as a fuel to create hydrogen from light hydrocarbons or natural gas, is the most typical methods**.** About fifty percent of the hydrogen generated worldwide is now produced by steam reforming of natural gas, which is currently the least expensive process [3]. Also of the same opinion, [21] believes that a large portion of the hydrogen in the globe is generated by this method, which is regarded as a cost-effective process in terms of product yield and energy usage. Therefore, they provide a simulated and optimized research of steam reforming procedure of an industrial natural gas based on MATLAB and Aspen HYSYS software. As a result, all of the variables were modified to properly operate a full procedure consisting of the equipment in the hydrogen generation areas (low-temperature gas shift, high-temperature gas shift reactor, and reformer reactor), as well as the units in the purifying region (methanator and absorber).

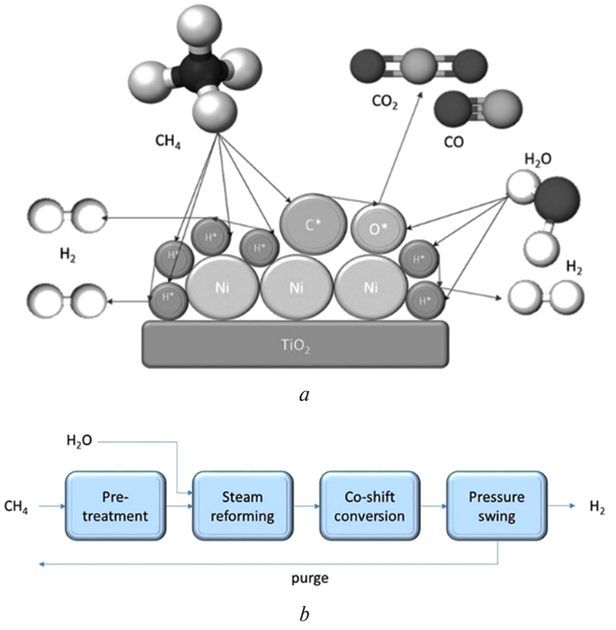

Fig. 3. Diagrams:

a – the SMR with Ni present on the TiO_2 support; b – the entire SMR procedure [20]

Paper [4] performed an overview of the techno-economic evaluation of different hydrogen generating processes. In this study, feedstock cost, H_2 economy, and worldwide energy requirements all play a role in the choice of feedstock for steam reforming. The endothermic procedure of steam reforming natural gas (SRNG) is more complex and needs high temperature supply (700–1,000 °C) for operation. The results indicated that the most effective, affordable, and efficient way to produce hydrogen is by natural gas steam reforming. [22] conducted technological and economical evaluation of distributed hydrogen generation from natural gas and concluded that natural gas is considered to be the greatest technologically and economically feasible fuel source for producing hydrogen in the short term before switching to sources of natural energy like biomass, solar energy, and wind energy. The findings revealed that natural gas is the most technologically and economically feasible raw material for producing hydrogen in the short term before switching to renewable energy sources like wind, solar, and biomass.

The composition of natural gas can vary significantly depending on the geologic reservoir from which it has been extracted, even though methane makes up the majority of its makeup. The number of contaminants in natural gas, such as nitrogen, water, higher-order hydrocarbons, and hydrogen sulfide can be determined by the location of the well, the geological conditions, and the extraction technique. [23] studied hydrogen creation through steam reforming from natural gas in a Pd-Au membrane system. After that, a comparison of the steam reforming reactions of methane and natural gas was performed. The obtained results show that the reforming reaction of natural gas outperformed the process of steam methane reforming, and reached over 80 % transformation of the higher hydrocarbons and a temperature of 450 °C and 300 kPa. In addition, to generate hydrogen with a high degree of purity, [24] conducted the steam reforming reaction of the natural gas under low conditions of operation in a synthetic palladium-based membrane unit. Furthermore, at low temperature, pressure, and sweep gas flow rate, the authors indicated the potential of a thin Pd-layer supported on PSS MR to generate a high purity hydrogen stream and high methane conversion via MSR reaction. Moreover, [25] proposed a system that shows possible benefits of the membrane reformer. This is Pd-based modern technology with a notional hydrogen generation capability of 40 Nm^3/h. The membrane reformer's initial operational test findings showed that CO_2 emissions reduced by more than 50 % with only a slight energy loss. In order to efficiently create hydrogen from natural gas, [26] developed the membrane reform system that has a 40 Nm^3/hr nominal hydrogen generation capacity. The system has shown the potential benefits of the membrane reformer: compactness, high energy efficiency of 70–76 %, and a simple system configuration made possible by the single-step synthesis of high-purity hydrogen (99.999 % level). In this study, the following are the reactions that transform city gas into mixes of hydrogen, carbon monoxide, and carbon dioxide: the shift process (4) and the steam reforming reaction (2 and 3), kj · mol^{-1}

$$C_nH_m + nH_2O \rightarrow nCO + (n + m/2)H_2 \quad (-\Delta H^0_{298} < 0); \tag{2}$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (-\Delta H^0_{298} = -206.2); \tag{3}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (-\Delta H^0_{298} = 41.2). \tag{4}$$

With an analysis of sorption-enhanced reforming, microreactors, and membrane reformers, [27] described a process for making hydrogen from natural gas by steam reforming. In this research, natural gas steam reforming is discussed using conventional plants and emerging trends, with an examination of membrane reformers, sorption-enhanced reforming, and microreactors. Also involved in analyzing reaction systems, [28] have conducted studies on the production of hydrogen by steam reforming methane and natural gas in microreactors and conventional reactor systems. For microreactor systems, similar Ni-based catalyst activities were measured in the steam methane reforming activity tests, but not in the natural gas steam reforming experiments. The obtained results indicated that the decentralized synthesis of hydrogen from natural gas can be accomplished using these sophisticated reaction systems.

According to [29], steam methane reforming (SMR) as a process for manufacturing hydrocarbon fuel makes up the majority amount of hydrogen yield in the world. Therefore they developed a three-dimensional computational fluid dynamics model and performed experimental verification of a small steam methane reformer to generate hydrogen from natural gas. In this method, the heated feed is introduced into the porous catalyst bed, which is the site of the SMR reactions. As shown in Fig. 4, the production gas that goes through the catalyst bed is gathered in the outer tube and exits through a single outlet. In order to improve the hydrogen production performances, [30] carried out the optimal design of a sleeved methane reformer reactor to generate hydrogen from natural gas. During production, the catalyst-bed and combustor were separated by a small sleeve, which allowed the feed and combustion gases to function as a counter-current heat exchange. Besides, to examine how the various operating variables or assumptions taken into account affect the performance of the hydrogen generation, [31] have built a comprehensive and detailed emulation model of an H_2 production facility using the sorption-improved reformation method. Moreover, in order to investigate how various operating circumstances or underlying assumptions affect plant performance, a comprehensive simulation model of an H_2 production plant based on the Sorption Enhanced Reforming process has been created in this study.

One main kind of steam-reforming catalyst is precious metal-based [32]. Thus, [33] has determined how well the thermal transfer efficiency of natural gas reforming by using steam in a reactor platform with a metal monolithic catalyzator compares to that in a traditional packed bed with a pellet. From that, the authors identified that when NGSR uses a monolithic catalyst bed reactor with these advantages in a small-scale H_2 fuelling station, it should be able to operate for on-site H_2 generation with a high throughput and much better financial benefits. In addition, the drawback of the procedure of reformation is that it must be pre-cleaned mostly of sulfur and nitrogen pollutants and this problem might be solved with natural gas that is liquefied [34]. Therefore, some studies use liquefied natural gas to extract hydrogen by steam reforming with a catalyst. Natural gas is purified throughout the liquefying process, mostly to remove carbon dioxide and water, to avoid solid particle formation when the gas is cooled to a temperature of roughly –160 °C (Fig. 5). While [35] utilized mesoporous Ni/Al_2O_3 catalysts made using the EDTA-assisted impregnation technique, [36] studied mesoporous $Ni–La–Al_2O_3$ aerogel catalyzator and evaluated the impact of La composition, [37] employed organized mesoporous nickel–alumina catalyzer in steam reforming to product hydrogen.

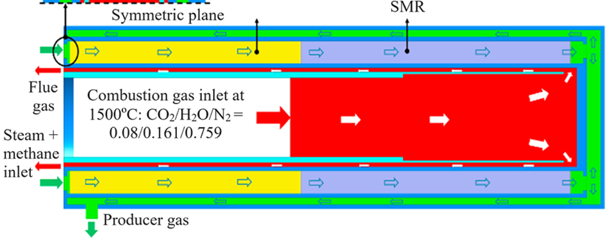

Fig. 4. The annulus SMR reactor structure features a sleeve positioned between the catalytic reactor and the combustor [29]

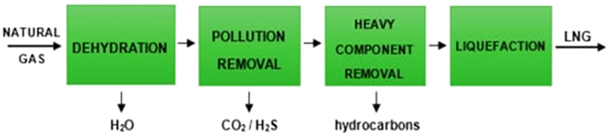

Fig. 5. The process of producing liquefied natural gas [34]

According to [38], hydrogen plays a crucial role as an energy source with no negative effects on the environment and creates a society with low carbon emissions. The problem may be solved by hydrogen separation membrane technology, which also offers effective carbon capture in hydrogen production. Thus, they have proven distributed carbon capture that is energy-efficient in the manufacture of hydrogen based on natural gas with the aid of innovative membrane reformer technology. Also involves a technical-environmental assessment of hydrogen production, [39] provided a technological and environmental perspective of producing hydrogen from biomethane and natural gas while capturing and storing CO_2. As a result, hydrogen produced from natural gas and electricity generated from renewable sources have the same environmental impact.

According to [40], a popular method for creating hydrogen is through the process for reforming natural gas using steam which consumes a significant quantities of energy and produces considerable amount of carbon dioxide. In order to reduce the release of carbon dioxide while manufacturing hydrogen, the natural gas dry reforming can be used as an alternative approach. While [40] presents the principle of hydrogen creation by dry reforming of CH_4 which utilizes kinetic and thermodynamic models, [41] studied theoretical thermodynamic restrictions of the whole natural gas conversion procedure via oxygen carrier reactions based on iron using methane. Energy is needed to produce hydrogen, and this process can result in process emitting, including fugitive emitted gases from a variety of resources, mostly accessories and pipeline devices. To provide a sequester-ready CO_2 stream in a carbon-constrained situation, two independent acid gas removal (AGR) CO_2 separation units are needed.

Despite being smaller than stack emissions, the emissions could still be dangerous to the environment and public health. [42] gives a calculation of fugitive emitting from the process of the natural gas steam reforming used to produce hydrogen. Also, using a precalculated modules technique, the amount of fugitive emissions of GHGs (CH_4 and CO_2) and CO from steam methane reforming operations was determined. According to [43], pollutant emissions from the production of industrial hydrogen may vary from theoretical estimations depending on the kind, condition, and process parameters of the installed pollution control equipment. Thus, they evaluated environmental influence of technology in hydrogen generation by steam methane reforming using natural gas. The findings show that the largest reduction of 78.1 % was identified in hydrogen production via biomass gasification, followed by 68.2 % in landfill gas and 53.7 % in hydrogen production derived from biomethane. Potential impact reductions can be observed when natural gas hydrogen production feedstock is replaced by sources of renewable energy. Because the environmental effect analysis concentrated on eutrophication, acidification, and greenhouse gas emissions, therefore, [44] assessed the influence on the environment of two techniques for producing hydrogen, including hydrogen produced through the biomass gasification and hydrogen produced through the steam reforming of natural gas. Findings show that biomass gasification has less of an impact than natural gas steam reforming for all three criteria, sometimes by a significant margin.

Hydrogen production via auto-thermal reforming of natural gas. The auto-thermal reforming procedure concerns the oxi-

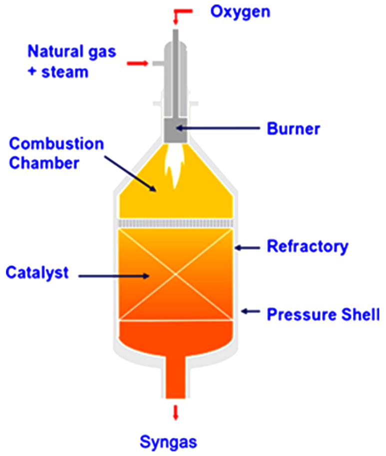

Fig. 6. A depiction of an autothermal reactor [46]

dation and shifting of natural gas in which the raw material reactions (catalytically) with steam in a single reactor and oxygen at sub-stoichiometric conditions [45]. In contrast to the Partial oxidation reforming process, the auto thermal reforming process was carried out at a lower pressure. Using the Partial oxidation process, the heat needed in the catalytic zone to propel the steam reforming processes has been produced. The components of the auto-thermal reactor are shown in Fig. 6. Table 3 displayed the reaction equations for the combustion chamber [46].

Similarly, [45] described the partial oxidization exothermic reaction that partially oxidizes natural gas as follows

$$CH_4 + 1/2O_2 \rightarrow CO + 2H_2 \qquad (5)$$

Paper [45] investigated the creation of hydrogen by the Auto-Thermal Reforming (ATR) process in conjunction with CO_2 collection utilizing an aqueous solution of Mono-Ethanolamine and the methanation process as a method of hydrogen purification. The authors discovered that, under a number of set operational assumptions, it is possible to produce 99 mol% pure hydrogen on a massive scale. This production is highly dependent on the temperature at which the ATR operates as well as the amount of CO_2 that is eliminated during the capture step. According to [47], a novel alternate technique for highly endothermic steam reforming does not require external heating is autothermal reformation (steam reforming) with the air supply to the reactor. Therefore, in order to demonstrate the value of enhancing autothermal reformers for hydrogen production, [47] used the non-dominated sorting genetic algorithm-II to simulate and improve hydrogen generation by natural gas autothermal reforming at low-pressure.

The research often takes into account both reforming process including steam reforming and ATR. Regarding temperature control and energy needs, ATR is believed to be simpler to operate. ATR can utilize the heat generated by the concurrent endothermic reforming reaction and exothermal oxidation. SMR is frequently utilized as the basis case, then ATR is added to demonstrate how better capture rates can be obtained [48]. However, the capital investment expense of the technology is increased by the requirement for air isolation equipment to provide oxygen for the partial oxidization process. [14] provides life cycle assessments and techno-economic analysis of four hydrogen generation methods that use natural gas as a feedstock. Fig. 7 shows the detailed block diagrams of technologies for producing hydrogen by ATR natural gas reforming.

Table 3

Simplified processes within the ATR combustion chamber [46]

Reactions	Reaction description	Standard enthalpy of reactions ΔH, $kj \cdot mol^{-1}$
$CH_4 + 3/2O_2 \rightarrow CO + 2H_2O$	Combustion	–519
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	Steam reforming	206
$CO + H_2O \leftrightarrow CO_2 + H_2$	Water gas shift	–41

Related to greenhouse gas emissions, [49] compared the technologies of steam methane reforming, ATR, and natural gas dissociation for the synthesis of blue hydrogen from natural gas. In this research, they explain how SMR, ATR, and NGD work. An outline of the procedures used to produce hydrogen is provided in Fig. 8. Each procedure consists of carbon collection, sequestration, hydrogen storage, transportation of CO_2, and hydrogen production units. Findings revealed that with 3.91 kg CO_2 eq/kg H_2, blue hydrogen produced by the ATR method emits the fewest greenhouse gases.

According to [50], when compared to endothermic steam methane reforming, the autothermal reforming (ATR) procedure for the creation of hydrogen uses significantly less energy in the reaction. Thus, they proposed an innovative ATR process that integrates an air extraction equipment and liquid natural gas regasification to employ cool power as an operational usage and create hydrogen from gas that is liquefied. [51] evaluated the most important recent technological and financial outcomes of hydrogen generation via natural gas reforming without as well as with carbon absorption. As a result, regarding energy and financial efficiency, the autothermal reforming process is less effective than the standard steam reforming technology (together with physical gas-liquid absorption for CO_2 collection).

In addition, it is impossible to handle simulations in three dimensions of an ATR system with exact chemistry due to computing disadvantages in relation to space and time resolution. Thus, under specified ATR operating conditions of natural gas, a method is provided by [52] to automatically produce optimized and reduced chemical schemes. In this study, in order to create target chemical responses that are indicative of the ATR flow arrangement, a novel model problem is con-

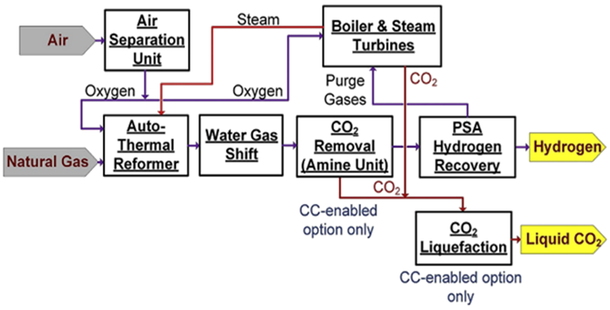

Fig. 7. Detailed block diagrams of technologies for producing hydrogen of ATR natural gas reforming [14]

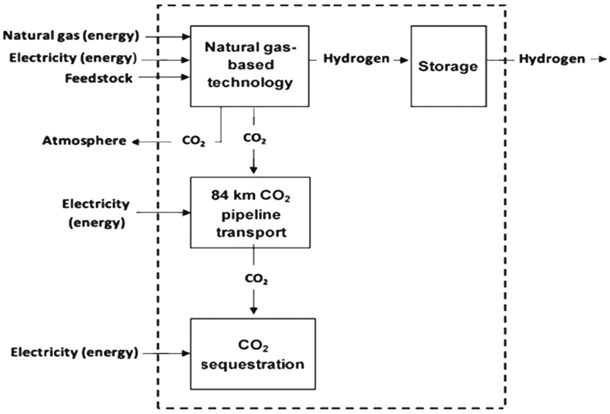

Fig. 8. An overview of technologies based on hydrogen [49]

structed. Next, an automated reduction scheme technique with the turbulence/chemistry relationship found in an ATR process is suggested and evaluated along these chemical paths. [53] utilized a new autothermal membrane fluidized-bed reactor that was incorporated into a 5-kWel micro-CHP system using a fuel cell made from PEM for hydrogen production. However, this methodology can show various risk situations. Therefore, they implemented a safety risk evaluation method to identify hazards that might exist during the autothermal reforming of natural gas for creating hydrogen in a membrane reactor and to detect incidents involving hydrogen under specific circumstances.

The principal concentration in reforming natural gas to create pure H_2 is linked to the current distribution system which can provide significant benefits for stationary power applications. With the goal to identify an effective, potential reactor design that uses autothermal reforming in conjunction with advanced catalysts to create tiny amounts of hydrogen from light hydrocarbons, [54] conducted research on using autothermal reformation of light hydrocarbons in conjunction with novel catalysts to produce hydrogen. This study specifically focuses on the analysis of performance data for a natural gas fuel processor used in stationary applications to produce 300–500 kW of electric power MCFC and convert it into hydrogen.

Outlook and remarks. According to the literature, the number of studies that have used the steam reforming method is significantly higher than that of the auto-thermal reforming approach to generate hydrogen. That means, steam reforming is the most popular industrial technique, with minimal need for oxygen, the smallest processing temperature, and the highest H_2/CO rate for producing H_2 [55]. Besides, this is the most affordable approach to create hydrogen. Its advantage results from its highly effective operation and low production and operational costs [12]. Steam reforming of natural gas yields hydrogen at a lower cost than alternative methods like steam reforming of biogas because it produces gas with a higher concentration of unconverted hydrocarbons (so-called tar) [56].

The outcomes of [22] demonstrated that natural gas steam reforming (SR) has a quicker payback period and a greater internal rate of return and return on investment. As a result, natural gas is compelled to serve as the most cost-effective and technically feasible materials for the manufacture of hydrogen in the near term, prior to the switch to alternative power sources like biomass, wind, and solar. Another advantage of this method is that natural gas steam reforming is the cheapest way to produce hydrogen, and it accounts for nearly half of hydrogen produced globally. The cost of feedstock, production volume, and other factors affect the cost of hydrogen produced by this approach [3].

The advantages of ATR are that it does not require heat from the exterior and is simpler and less costly than steam reforming of methane. Moreover, it can be discontinued and restarted very fast and still produce more hydrogen than partial oxidation alone. This is another important benefit of ATR over steam reforming [12]. On the other hand, autothermal reforming has the benefit of requiring low process temperature and low methane slip but needing air or oxygen [55]. Moreover, when comparing the autothermal reforming process to endothermic steam methane reforming, a significant amount of energy is saved during the reaction. Nevertheless, an air separation unit (ASU) is required in order to provide the clean oxygen supply that it demands. Therefore, ATR is not widely adopted in industrial applications owing of the high capital and operating expenses [56].

Hydrogen has been identified as the potential and cleanest sources of energy for the twenty-first century. Furthermore, it is a crucial chemical substance that is utilized extensively in industries. At present, a wide range of workable methods for producing hydrogen have been developed. However, this technology has several drawbacks such as considerable pollution, considerable energy consumption, weak conversion efficiency, and high pollutant levels in products [13]. Currently, although steam reforming is one of the most widely used and least expensive methods for generating hydrogen, the following factors should be considered in future research to overcome the current challenges. Firstly, in order to create significant theoretical progress, interfacial engineering techniques can be used to study the steam reforming of hydrocarbons from a microscopical viewpoint of molecular engineering techniques [57]. Furthermore, computer simulations and modeling play a crucial role in forecasting, assessing, and refining different hydrogen-production techniques, thereby improving efficiency and lowering production expenses [58]. Additionally, the literature found that steam reforming is a complicated reaction. However, this problem can be addressed by creating a suitable catalyst and operating process. Some catalysts with improved function can be created by adjusting several factors, including particle dimension, suitable supporters, assisting substances, and modifying cooperation condition in the study of [20]. Additionally, the precleaning requirement for the reforming process, which removes predominantly sulfur and nitrogen molecules, is also a drawback. Liquefied natural gas has recently attracted consideration a potential energy source and natural gas substitute. Thus, liquefied natural gas might be the solution to this issue [34].

Recently, there has been a trend to integrate machine learning (ML) into the process of hydrogen production. The growth of ML has made it possible to apply ML to several areas of hydrogen research, including process modeling, optimization, and soft-sensor creation, in the production of hydrogen. Furthermore, the application of ML in process modeling and optimization of adsorption processes, such pressure swing adsorption (PSA), which is employed in the manufacture of hydrogen to produce high-purity H_2, has been popular recently [59]. Compared to traditional process modeling, machine learning (ML)-based models can yield robust and efficient models [60]. In the future, research should concentrate on incorporating ML into hydrogen production process to speed up the development of blue hydrogen generation materials and procedures. This is essential to assure a low carbon future.

Conclusion. This review provides a detailed understanding of hydrogen production from natural gas. The two hydrogen production methods along with their advantages and disadvantages are carefully analyzed based on studies published since 2010. Findings reveal that hydrogen production by steam reforming of natural gas is used more than the method based on automatic thermal reforming.

It is notable, steam reforming of natural gas has the worst effects on the environment with regard to abiotic degradation, probable global warming, and other influence types. Even though the costs of producing hydrogen through steam reforming are quite affordable, the expenses associated with the impact on the community are very significant. Thus, it is recommended that further research should pay more attention to environmental pollution when producing hydrogen.

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Огляд виробництва водню за допомогою риформінгу природного газу

*Дуен Куанг Ле**[1], *Нгуен Тхе Дзунг*[2]

1 – Факультет нафти та енергетики, Ханойський університет гірництва і геології, м. Ханой, Соціалістична Республіка В’єтнам

2 – Відділ петрографії та петрофізики Дослідно-інженерного інституту, Спільне підприємство В’єт-Нга В’єтсовпетро, м. Вунгтаун, Соціалістична Республіка В’єтнам

* Автор-кореспондент e-mail: lequangduyen@humg.edu.vn

Мета. Надати всебічний аналіз виробництва водню, а також його основних переваг і труднощів при виробництві водню із природного газу.

Методика. У даному дослідженні був використаний підхід систематичного огляду. Перший етап у комплексному оцінюванні полягає в пошуку значущих робіт і конкретних концепцій, пов’язаних із даним питанням, а потім у застосуванні їх стосовно пошукових фраз і синтаксису. Ретельний пошук здійснюється в базах даних Web of Science, Google Scholar, Science Direct і Scopus англійською мовою. Крім того, час публікації статей обмежено періодом із 2010 року до вересня 2023 року.

Результати. Аналіз літературних джерел виявив, що риформінг природного газу є найпоширенішим способом виробництва водню. Отримані результати також показали, що підхід на основі автоматичного термічного риформінгу є менш поширеним, ніж той, який використовує природний газ для виробництва водню паровим риформінгом. Крім того, паровий риформінг природного газу має найбільший негативний вплив на навколишнє середовище, ураховуючи абіотичний розклад, потенційне глобальне потепління та інші види впливу.

Наукова новизна. Даний аналіз пропонує детальний огляд того, як виробляється водень із природного газу, а також переваги та обмеження методу риформінгу для виробництва водню.

Практична значимість. З огляду літератури виявлено, що сучасний найбільш уживаний метод створення водню – це паровий риформінг природного газу. Крім того, цей огляд надає вичерпний і корисний ресурс для вивчення, наукового розвитку та просування в галузях створення водню.

Ключові слова: *виробництво водню, природний газ, паровий риформінг, автотермічний риформінг*

The manuscript was submitted 13.10.23.