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Plasma processing methods for hydrogen production[⋆]

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Abstract. In the future a transfer from the fossil fuel-based economy to hydrogen-based economy is expected. Therefore the development of systems for efficient H_2 production becomes important. The several conventional methods of mass-scale (or central) H_2 production (methane, natural gas and higher hydrocarbons reforming, coal gasification reforming) are well developed and their costs of H_2 production are acceptable. However, due to the H_2 transport and storage problems the small-scale (distributed) technologies for H_2 production are demanded. However, these new technologies have to meet the requirement of producing H_2 at a production cost of \$(1–2)/kg(H_2) (or 60 g(H_2)/kWh) by 2020 (the U.S. Department of Energy's target). Recently several plasma methods have been proposed for the small-scale H_2 production. The most promising plasmas for this purpose seems to be those generated by gliding, plasmatron and nozzle arcs, and microwave discharges. In this paper plasma methods proposed for H_2 production are briefly described and critically evaluated from the view point of H_2 production efficiency. The paper is aiming at answering a question if any plasma method for the small-scale H_2 production approaches such challenges as the production energy yield of 60 g(H_2)/kWh, high production rate, high reliability and low investment cost.

1 Introduction

Currently more than 80% of the world energy supply comes from fossil fuels, resulting in strong ecological and environmental impacts. Such factors as the exhaustion of reserves and resources, air pollution and modification of the atmospheric composition, impacts on climate and human health, are now of primary importance. It is a wide opinion that hydrogen has a great role to play as an energy carrier in the future energy sector.

Several processes have been developed for producing hydrogen mainly from fossil fuels and to some extent from water. Hydrogen can be produced from fossil fuels (or biomass and biomass-derived fuels) using such processes as steam reforming (mainly of natural gas), partial oxidation, auto-thermal reforming, and coal gasification. From any primary energy source (nuclear, wind, solar) converted into electricity hydrogen can be produced by the electrolysis of water. Hydrogen can also be produced using photochemical energy (photo-catalysis, bioconversion). More on various technologies related to hydrogen production by a so-called conventional methods can be found in a review presented in reference [1].

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Currently the USA and Japan are investing in R&D programmes on hydrogen technology and fuel cells. Also the European Union has presented a European roadmap for the production and distribution of hydrogen, as well as for fuel cells and hydrogen systems [2]. According to the European Commission vision of 2005 the transition to the hydrogen economy should proceed along the following steps.

In the first term to 2010, which has already passed, hydrogen and fuel cells should have been applied in several niche markets.

In the second term from 2011 to 2020, currently running, an increased production of hydrogen, still from fossil fuels, should be obtained. However, an increased production of hydrogen from renewable energy sources will be fostered. Owing to the increased availability of hydrogen the use of hydrogen as a fuel in modified conventional combustion engines and (or) fuel-cell systems in cars and trucks is expected.

In the next term, beyond 2020 a growing production of hydrogen will accompany an increasing demand of consumers for clean energy supply. Both electricity and hydrogen will progressively replace the outdated carbon energy system. Renewable and nuclear energy sources will gradually substitute fossil fuels.

One of the most advanced assessment of the present hydrogen policy has been made by the U.S. Department of Energy (DOE) [3]. The aim of this policy is to identify research pathways leading to hydrogen production technologies that produce near-zero net greenhouse gas emissions and use renewable energy sources, nuclear energy, and coal (with carbon dioxide capture and storage).

To analyse the future of hydrogen technology development it is convenient to divide the facilities for hydrogen production in three scales: small, medium and large. Small-scale facilities, called also distributed would produce from 100 to 1500 kilograms (kg) of hydrogen per day at the point of use (e.g., fuelling stations). Medium-scale (also known as semi-central or city-gate) facilities would produce from 1500 to 50 000 kg per day on the outskirts of cities. The largest (central) facilities would produce more than 50 000 kg of hydrogen per day.

According to the DOE the current hydrogen production cost targets are $3.00 per kilogram of hydrogen at fuelling stations and $2.00 per kg of hydrogen at a central facility (a kilogram of hydrogen is approximately equal to a gallon (3.79 L) of gasoline equivalent (gge) on an energy content basis). At present the cost of production of a gallon of gasoline is about $2 in the USA (excluding delivery, storage and tax).

Centralized natural gas reforming development is not being pursued by the DOE because it is already an established commercial technology with a cost of $2.00 per kg of hydrogen (currently most of the worldwide hydrogen production, more than 90%, originates from the large-scale steam reforming of natural gas). However, due to growing hydrogen demand alternative large scale (centralized) hydrogen production facilities will be needed. The DOE is pursuing central production of hydrogen from a wide diversity of feedstocks (including nuclear energy and renewable sources) and processes (coal gasification with carbon sequestration to reduce or eliminate greenhouse gas emissions, biomass gasification, next generation nuclear energy high temperature sulphur-iodine thermochemical process, next generation nuclear energy high temperature steam electrolysis, current nuclear energy using standard electrolysis, and wind electrolysis).

Distributed hydrogen production may be the most viable approach for introducing hydrogen as an energy carrier because it does not require a substantial transport and delivery infrastructure or large capital investments. In this case such technologies as natural gas reforming, electrolysis, reforming of ethanol and methanol (both from biomass) are pursued by DOE.

Table 1 shows DOE's envisage of hydrogen production targets in the distributed and central scales for the period 2011–2020. According to it the ultimate hydrogen production cost target is $1 - $2 per kilogram of hydrogen (a cost goal of about $2 per kg of hydrogen has been identified as the range at which delivered hydrogen becomes cost competitive with gasoline for passenger vehicles). The DOE predicts that such a cost target will be difficult to achieve for technologies based on solar thermochemical, photoelectrochemical and biological processes.

Recently another technology has been proposed for distributed hydrogen production [4,5]. This technology uses thermal and non-thermal plasmas for reforming gaseous and liquid compounds containing hydrogen. They can originate from fossil fuels and biomass. The observed increasing interest in liquid fuels [5] for hydrogen production has arisen because they can provide significant advantages due to a high hydrogen to carbon ratio, low boiling point, low temperature for conversion to hydrogen, no sulphur content, high water solubility and biodegradability [6]. However, DOE's scenario has not predicted any role for the plasma technology in the future roadmap towards the hydrogen-oriented world economy so far.

This paper is an assessment of the plasma methods proposed for hydrogen production using gaseous and liquid (mainly vapourized) fuels from the view point of hydrogen production efficiency determined by such parameters as the thermodynamic limit of H_2 energy yield [g(H_2)/(kWh)], hydrogen production rate (g(H_2)/h) and energy yield [g(H_2)/(kWh)]. The paper is aiming at answering a question if any plasma method for the small-scale H_2 production is capable of fulfilling the DOE's criterion of practical applicability in 2020, i.e., being capable of producing H_2 at a production cost of \$(1–2)/kg(H_2). According to this aim, the selection of literature cited in this paper is limited to those papers which showed the highest energy-related characteristics of the proposed plasma processing (thermodynamic limit of H_2 energy yield, production rate g(H_2)/h, energy yield g(H_2)/kWh), which could compete with the well-established processes for hydrogen production and meet the requirements of the US Department of Energy for 2020. Numerous other papers on plasma hydrogen production, in particular old ones, had given little consideration to the production cost of hydrogen.

2 Hydrogen production by plasmas from gaseous and liquid (vapourized) fuels

2.1 Thermodynamic and kinetic limits

One of the most important problems of hydrogen production is the minimization of energy consumption. This results in tough requirements for the energy efficiency of the plasma-chemical processes oriented towards hydrogen production to be competitive with other technologies.

The energy efficiency of a specific plasma-chemical process is the ratio of the thermodynamically minimal cost of the process to the actual energy E_{act} consumed in the process. Usually the minimal cost of the process is the reaction enthalpy ΔH.

The thermodynamically minimal cost of the process is often referred to as *the thermodynamic limit of energy consumption* of the reaction.

The energy efficiency of 100% corresponds to the thermodynamically lowest cost of the reaction. The energy efficiency of the quasi-equilibrium plasma-chemical reactions performed in thermal discharges is usually less than 10–20% [7], while that of non-equilibrium reactions can be higher, mainly due their lower gas temperatures that choke off the reverse processes.

Table 1. DOE's envisage of hydrogen production targets in distributed and central scales for the period 2011–2020 [3].

	$/kg (production costs only)	2011 Status target	2015 target	2020 target	Ultimate production target
Distributed	Electrolysis from grid electricity	$4.20	$3.90	$2.30	
	Bio-derived Liquids (based on ethanol reforming case)	$6.60	$5.90	$2.30	
Central	Electrolysis from renewable electricity	$4.10	$3.00	$2.00	$1–$2
	Biomass gasification	$2.20	$2.10	$2.00	
	Solar thermochemical	NA	$14.80	$3.70	
	Photoelectrochemical	NA	$17.30	$5.70	
	Biological	NA	NA	$9.20	

The energy efficiency of plasma-chemical processes depends strongly on their kinetics, in which the reverse processes play an important role. The reverse processes can convert the products back into initial substances. Conservation of the products of plasma-chemical processes requires the application of very fast cooling, called quenching phase of the overall reaction process, to protect the products from reverse reactions. In reference [7] three specific quenching modes for analyzing the energy efficiency of the quasi-equilibrium plasma-chemical processes: absolute quenching, ideal quenching and super-ideal quenching were introduced. Due to the quenching the total degree of conversion of the substances into the products can not only be saved, but it can be increased. The reaction kinetics of the plasma-chemical process determines the so-called *kinetic energy efficiency*, also known as the *kinetic limit of energy efficiency* of the process. The kinetic limit energy efficiency of plasma-chemical processes is usually lower than that determined by the thermodynamic limit.

Apart from the energy efficiency of a specific process, *the energy yield* E_y of the process is an important energy parameter that determines competitiveness of the process. The energy yield of the process is the ratio of the product mass M_{prod} to the actual energy E_{act} consumed in the process.

Another parameter that characterizes a specific process is *the production rate* of the product. It gives the mass of product which is produced in a unit of time.

Table 2 shows the energy parameters (standard reaction enthalpy (in eV/molec or kJ/mol) and thermodynamic limit of H_2 energy yield [in $g(H_2)/(kWh)$]) of selected plasma chemical processes of the conversion of gaseous and liquid fuels into hydrogen (for comparison also the parameters of carbon steam reforming process are shown).

The methods of production of hydrogen using plasma, shown in Table 2, are divided into four approaches: pyrolysis, dry reforming, steam reforming and partial oxidation. The pyrolysis (called also the direct decomposition) of hydrocarbons or other oxygen-free compounds results in carbon and hydrogen. The compounds containing oxygen, e.g., alcohols may decompose into oxygen compound and hydrocarbon, often into carbon oxide and hydrogen, i.e., into syngas. The dry and steam reforming result in syngas (or a mixture of carbon dioxide and hydrogen when the water-gas shift occurred). The partial oxidation usually produces syngas, sometimes accompanied by water vapour.

The hydrogen energy yields of a given reaction for the case of the thermodynamic limit of energy consumption, shown in Table 2, can be compared with DOE's target 2020 for hydrogen energy yield, which is 60 $g(H_2)/kWh$ [an equivalent to a cost of $2 per kg of hydrogen, assuming that pricing of 1 kWh of electric energy is $0.12; obviously when the pricing of 1 kWh of electric energy is lower due to availability of a cheap energy source (e.g., from solar or wind farms), the DOE's target 2020 will be more advantageous for the plasma production of hydrogen]. From this comparison a first selection of candidates as potential fuel for the plasma hydrogen production can be done, remembering, however, that the practically achievable results will be worse due to the actual energy efficiency of the plasma-chemical process and the production system.

According to Table 2, the DOE's 2020 requirement can be met when methane is reformed in the pyrolysis and steam reforming, while the straightforward dry reforming of methane is excluded as an efficient process for hydrogen production. Although higher hydrocarbons apparently provide a significant advantage for hydrogen production, having a high hydrogen to carbon ratio, some of them do not meet the DOE's requirement, e.g., octene in the pyrolysis process. In contrast, alcohols, in particular methanol, exhibit rather high values of the thermodynamic limit of hydrogen energy yield. This suggests that alcohols seem to be promising feedstock for hydrogen production, and the alcohol-based plasma-chemical systems may reach DOE's target 2020 of hydrogen energy yield, even if their energy efficiency would be about 30%.

2.2 Experimental data on hydrogen production by plasmas from gaseous and liquid (vapourized) fuels

Although plasma methods have not been predicted by the U.S. DOE as a future method for hydrogen production, a substantial amount of research has been pursued in the development of plasma-based hydrogen generation systems. The plasmas proposed for hydrogen production from gaseous or liquid (vaporized) fuels were generated by: electron beam, dielectric-barrier discharges, spark discharges, gliding, plasmatron and Laval nozzle arcs, and microwave

Table 2. Standard reaction enthalpy and thermodynamic limit of H_2 energy yield of selected plasma chemical processes of the conversion of gaseous and liquid fuels into hydrogen (for comparison carbon steam reforming reaction is included).

Processes	Reaction	Standard reaction enthalpy		Thermodynamic limit of H_2 energy yield
		eV/molec.	kJ/mol	g(H_2)/kWh
DOE's Target 2020 for H_2 energy yield – 60 g(H_2)/kWh				
Pyrolysis				
Methane	$CH_4 \rightarrow C(s) + 2H_2$	0.7 [7]–0.9 [21]	75	192
Propane	$C_3H_8 \rightarrow 3C(s) + 4H_2$	1.3 [14]	125	230.4
Octene	$C_8H_{16} \rightarrow 8C(s) + 8H_2$	12.5 [14]	1204	47.8
Methanol	$CH_3OH \rightarrow CO + 2H_2$		291 [31]	
Water vapour	$H_2O(g) \rightarrow 0.5O_2 + H_2$	2.6 [7]	250	28.8 [31]
Water vapour	$2H_2O(g) \rightarrow H_2O_2 + H_2$	3.2 [7]	308	23.4 [31]
Water (liquid)	$H_2O(l) \rightarrow 0.5O_2 + H_2$	2.95 [37]	284	25.4
Dry reforming				
Methane	$CH_4 + CO_2 \rightarrow 2CO + 2H_2$	2.6 [7]	250	57.8
Steam reforming				
Methane	$CH_4 + H_2O \rightarrow CO + 3H_2$	2.2 [21]	206	103
Methane	$CH_4 + H_2O \rightarrow CO + 3H_2$ $CO + H_2O \rightarrow CO_2 + H_2$ With water-gas shift reaction		165	
Propane	$C_3H_8 + H_2O \rightarrow CO + 3H_2$	5.4 [21]	520	41.5
Octene	$C_8H_{16} + 8H_2O \rightarrow 8CO + 16H_2$	12.5 [21]	1204	95.7
Methanol	$CH_3OH(l) + H_2O(l) \rightarrow CO_2 + 3H_2$	0.7 [21]	67.6 [21], 90.7 [31,36]	238 [31,36]
Ethanol	$C_2H_5OH + H_2O \rightarrow 2CO + 4H_2$	2.6 [7]	250.4	115
Carbon	$C(s) + H_2O \rightarrow CO + H_2$	1.3 [21]	125	57.5
Partial oxidation				
Methane	$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	−0.2 [21]	−19.3	
Methane	$CH_4 + 0.5O_2 + 0.5CO_2 \rightarrow$ $1.5CO + 1.5H_2 + 0.5H_2O$ Auto-thermal reforming		~0	
Methane	$CH_4 + 0.25O_2 + 0.5H_2O \rightarrow CO + 2.5H_2$ Auto-thermal reforming		~0	
Propane	$C_3H_8 + 1.5O_2 \rightarrow 3CO + 4H_2$	−2.1 [21]	−202	
Octene	$C_8H_{16} + 4O_2 \rightarrow 4CO + 8H_2$	−9.9 [21]	−953	

discharges. Currently, the most interest lies in the plasma reforming of hydrocarbons and alcohols. Among hydrocarbons methane is the most popular gaseous fuel used in the study of plasma production of hydrogen. The reforming of methane for producing hydrogen has been investigated in plasmas produced in dielectric barrier discharges [8–10], electron beam radiolysis [11], gliding arc [12], plasmatron arc [13], microwave discharges [14–16] and spark discharge [17]. Alcohols (methanol, ethanol and propanol) have been used as a feedstock in various research plasma systems based on dielectric barrier discharges [8], surface wave discharges [13], AC discharges [18–20], microwave discharges [21,22], glow discharges [23], silent discharges [24,25], corona discharges [26,27], gliding arcs [28–31], plasmatron arc [29], discharges in liquids [28] and Laval nozzle arc [32].

Table 3 summarizes to some extend the plasma technologies, along with their feedstocks and energy efficiencies, tested for hydrogen production. It shows the hydrogen production rate and energy yields for most used gaseous and liquid (vapourized) feedstocks. For comparison, also data on the energy parameters of the conventional steam reforming of methane (with a catalyst) and water electrolysis are given in Table 3.

Regarding the plasma methods based on methane feedstock, shown in Table 3, the plasma generated by a plasmatron arc [13] seems to be most promising technology of hydrogen production from methane on an energy yield basis [280 g(H_2)/kWh versus the 2020 target of 60 g(H_2)/kWh]. However, this method presented in 2000 has not been reported afterwards as successfully implemented. The gliding arc processing of methane [12] offers an energy yield similar to that of water electrolysis (40 g(H_2)/kWh), however, at present the both methods do not reach the target of 60 g(H_2)/kWh. The electron beam radiolysis [11] and dielectric barrier discharges [8–10] are low energy efficient and far from reaching the DOE's 2020 target. The spark discharge [17] exhibits promising energy yield but its production rate is low. More promising technology for hydrogen production from methane seems to be microwave plasmas. It was shown [15] that the use of the so-called waveguide-supplied metal-cylinder-based microwave plasma source resulted in a hydrogen production energy yield of 42.9 g(H_2)/kWh. A higher energy

Table 3. Conventional and plasma methods of H_2 production. Comparison of the hydrogen production rates and energy yields.

Production method	Initial composition	Production rate g(H2)/h	Energy yield $g(H_2)$/kWh	References
		Gaseous fuel		
Conventional steam reforming of methane (catalyst)	$CH_4 + H_2O$ + air		60 Established industrial process	Randolph, U.S. DOE, 2013 [3]
Electron beam radiolysis	$CH_4 + H_2O$		3.6	Kappes et al., 2003 [11]
Dielectric barrier discharge	CH_4 + air	0.13	6.7	Heintze and Pietruszka, 2004 [9]
Dielectric barrier discharge	$CH_4 + CO_2$	0.25	5.2	Dors et al., 2012 [10]
Dielectric barrier discharge	$CH_4 + CO_2/H_2O$		0.5	Sarmiento et al., 2007 [8]
Spark discharge	$CH_4 + CO_2$	0.4	17.3	Shapoval et al., 2014 [17]
Gliding arc	$CH_4 + H_2O$ + air		40	Cormier and Rusu, 2001 [12]
Plasmatron arc	$CH_4 + H_2O$ + air		280	Bromberg et al., 2000 [13]
Metal-cylinder-based microwave plasma	$CH_4 + CO_2 + H_2O$	180	42.9	Jasiński et al., 2013, 4.5 kW [15]
Waveguide supplied resonant-cavity-based microwave plasma with catalyst	$CH_4 + H_2O$	169	62.8	Jasiński et al., 2014, 2.5 kW [16]
		Liquid (vaporized) fuels		
Water electrolysis	H_2O		20–40	Randolph, U.S. DOE, 2013 [3]
Gliding arc (water spray)	H_2O + Ar	0.004	13	Burlica et al., 2010 [30]
Dielectric barrier discharge	$CH_3OH + CO_2/H_2O$ $CH_3CH_2OH+CO_2$		3.3 6.7	Sarmiento et al., 2007 [8]
Gliding arc (alcohol spray)	CH_3OH + Ar	0.08	176	Burlica et al., 2011 [31]
Laval nozzle arc	$C_2H_5OH + H_2O$	18	100	Du et al., 2012 [32]
Microwave (2.45 GHz) plasma	CH_3OH + Ar $C_2H_5OH + H_2O$ + Ar	0.6 0.3	1.4 0.5	Henriques et al., 2011 [39]
Microwave (2.45 GHz) plasma	C_2H_5OH + Ar		0.55	Tsyganov et al., 2013 [40]
Microwave (2.45 GHz) plasma	CH_3OH + Ar $C_2H_5OH + H_2O$ + Ar		0.29 0.41	Bundaleska et al., 2013 [38]
Microwave (915 MHz) plasma	$C_2H_5OH + N_2$	95.7	22.2	Jasiński et al., 2015 [34]
Microwave (915 MHz) plasma	$C_2H_5OH + CO_2$	59.5	11.9	Jasiński et al., 2015 [34]
Microwave (915 MHz) plasma	$C_3H_7OH + CO_2$	92.9	18.9	Jasiński et al., 2015 [34]

yield of 62.8 $g(H_2)$/kWh, i.e., above the DOE's 2020 target, was obtained in a waveguide supplied resonant-cavity-based microwave plasma source with a support of catalyst [16]. Both these methods exhibit the hydrogen production rates much higher than those of the other methods presented in Table 3. It seems that the relatively high values of the hydrogen production rate and energy yield demonstrated by the microwave methods used for hydrogen production from methane [15,16] make these methods attractive for further development towards approaching the DOE's 2020 target.

Since the thermodynamic limits of the energy yield for hydrogen generation from alcohols are high (Tab. 2) one can expect that the energy yield of hydrogen production from alcohols by plasma methods should be also high. Table 3 shows that the experimental hydrogen energy yield from methanol using gliding arc systems can be as high as 100 $g(H_2)$/kWh for ethanol as fuel [32] and 176 $g(H_2)$/kWh for methanol [31]. However, the method presented in reference [31] exhibits a very low hydrogen production rate. Nevertheless, these results clearly show that plasma reforming of liquid fuels can be attractive in terms of the energy efficiency.

As seen from Table 3, recently the microwave plasmas operating at atmospheric pressure have recovered interest as a potential method for hydrogen production from alcohols. Using the waveguide-supplied metal-cylinder-based microwave plasma source (915 MHz) with an unoptimized alcohol delivery system [33] a hydrogen energy yield of about 20 g(H_2)/kWh was obtained from ethanol and isopropanol. It is worth noting that using the same microwave plasma a relatively high hydrogen production rate up to 100 g(H_2)/h was obtained [34]. The very similar results were obtained using the waveguide-supplied metal-cylinder-based microwave plasma source operating at 2.45 GHz [35].

Summarizing, although some improvement in the development of plasma-chemical systems for hydrogen production regarding the energy parameters is observed, the plasma systems are still far from practical implementation.

3 Conclusions

As shown, the economic analysis of the U.S. Department of Energy has determined tough conditions for hydrogen production technologies to be accepted in the distributed and central scales by the market in 2020. The most important requirement which has to be met by the hydrogen producers in the distributed scale is the energy yield of 2 US$ per kg of hydrogen (equivalent to 60 g(H_2)/kWh) in 2020. DOE expects that such technologies as natural gas reforming, electrolysis from grid electricity, reforming of ethanol and methanol (both from biomass) are capable of targeting 2 US$ per kg of hydrogen in 2020. Plasma technologies have not been mentioned by the DOE's report as an economically competitive technology for hydrogen production.

At present some plasma technologies have met the DOE's energy yield requirement foreseen for 2020. In the case of distributed hydrogen production from gaseous and liquid fuels they are: gliding, plasmatron and nozzle arcs and microwave discharges (Tab. 3). However, higher expectations are placed on these technologies when liquid fuels are to be used as a source of hydrogen.

Although the use of catalyst may result in substantial increase of the hydrogen production yield [6], opinions on catalyst potential to be commercially attractive in supporting the plasma production of hydrogen are divided. Some claim unpracticality of using catalysts which are expensive and impurity vulnerable.

Apart from the hydrogen production rate and energy yield other factors have to be considered when assessing the usefulness of plasma technology for the commercial production of hydrogen. These are: fuel conversion, CO_2 emission (the industrially well-established steam reforming of methane and partial oxidation of hydrocarbons generate large quantities of CO_2), carbon deposit, cost of hydrogen extraction from the post-processing gas, and investment and running costs. Generally there is lack of such information in the literature. A relatively well-developed cost model of hydrogen production was presented for the plasmatron technology in reference [13]. The conclusion from this cost assessment is that although the plasmatron method is very efficient in hydrogen production, the investment and running costs for this approach are relatively high.

Summarizing, at present, i.e., about 5 years before a milestone year 2020 determined by the U.S. DOE, some plasma methods for small-scale (distributed) hydrogen production from gaseous fuels seem to cross the energy yield target of 60 g [H_2]/kWh. However these methods have to meet the challenge of the high hydrogen production rate, high reliability and low investment cost. Therefore, significant progress has to be made in development of plasma hydrogen production systems, more technical progress and cost reduction need to occur for them to compete with traditional reforming technologies. There are opinions that the plasma hydrogen production belongs to longer term technologies in terms of implementation maturity, similarly as biohydrogen approach, thermochemical and photoelectrochemical water splitting, and photoelectrolysis.

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