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Review Article

A comprehensive review on hydrogen production from coal gasification: Challenges and Opportunities

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HIGHLIGHTS

- Hydrogen production from coal is efficiently conducted by applying gasification techniques.
- Energetic, economic, environmental and sustainability aspects are important for better evaluating the gasification methods.
- For a higher amount of hydrogen production from low quality coal, plasma gasification technique can be a more efficient and effective solution.
- Plasma gasification process results in less wastes compared to other gasification processes.
- Plasma gasification is more environmentally friendly, more efficient and hence more sustainable than other gasification methods.

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ABSTRACT

This paper comparatively discusses hydrogen production options through coal gasification, including plasma methods, and evaluate them for practical applications. In this regard, it focuses on numerous aspects of hydrogen production from coal gasification, including (i) state of the art and comparative evaluation, (ii) environmental and economic dimensions, (iii) energetic and exergetic aspects, (iv) challenges, opportunities and future directions. Furthermore, this review paper outlines what differences it brings in and what contributions it makes to the current literature about such a significant domain of potential hydrogen production which can be used as clean fuel, energy carrier and feedstock. Accordingly, this comprehensive review offers some results as follows: (i) plasma gasification system produces higher amount of hydrogen from other gasification processes, (ii) less amounts of solid wastes (slag, ash, tar, etc.) are released during plasma gasification process compared to other gasification processes, and (iii) it is overall more sustainable Thus, plasma gasification is proposed as a potential option for hydrogen fuel production from coals and for practical application in energy sector. As a case study, some plasma gasifiers in the literature are analyzed in terms of the exergetic sustainability. Furthermore,

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the case study results show that the exergetic sustainability index decreases from 0.642 to 0.186, and the exergetic efficiency drops from 0.342 to 0.156, while the environmental impact factor increases from 1.556 to 5.372 with an increase of waste exergy ratio from 0.839 to 0.532, respectively.

Contents

Introduction

Gasification is recognized as the process converting any carbon-based raw material into synthetic gas using air, water vapor or oxygen [1–4]. Using gasification techniques, many raw materials and wastes, such as coal, car tires, sewage sludge, sawdust, wood and plastic waste can easily and effectively be converted into useful outputs [5–9]. At the end of any gasification process, a product gas may include some or all of the outputs that may generally contain CO, H_2, CH_4, ash, tar, H_2S, NH_3, HCl and HCN [10]. The product gas then needs to be purified from the contaminants, particles and some other substances which really decrease its calorific value by applying various gas clean-up processes, and the useful gases, such as CO, H_2 and CH_4 are separated accordingly [10]. In the gasification process, it is clear that four different types of coal are generally utilized in a suitable manner [11,12], which are (i) lignite (low rank), (ii) sub-bituminous coal (low rank), (iii) bituminous coals (medium rank), and (iv) anthracites (high rank). However, it is important to note that, according to the open literature, these materials are generally gasified at higher temperatures than 900 °C [10] by applying the following techniques: (i) fixed bed gasification, (ii) moving bed gasification, (iii) fluidized bed gasification, (iv) entrained flow gasification and (v) plasma gasification. Among these gasification processes, the entrained and plasma gasification of coal may generally be carried out at higher temperatures between 1200 and 1700 °C, respectively [10,13–15]. However, the others may require lower operating temperatures than 1200 °C.

Coal gasification appears to be a significant process for cleaner and more cost-effective generation of energy and other chemical products [16], where the following advantages come to forefront compared to the traditional coal combustion processes:

- Coal gasification converts more efficiently the high moisture and ash content of coal into useful outputs [17].
- Coal gasification provides synthesis gas production with high calorific value [18].
- Electricity can be produced more efficiently by using hydrogen-rich gas as a result of coal gasification [19].
- As a result of coal gasification, carbon emissions are considerably decreased [20,21].

Among the coal gasification methods, plasma gasification is recognized as a relatively new technology using plasma torch in order to produce clean and renewable fuels [22]. During the process, the raw material in the system are decomposed [23]. Due to very high temperature, higher conversion efficiency can potentially be achieved. The products released during the process are essentially syngas and slag [24]. Under these considerations, some key advantages of plasma gasification can be summarized as follows.

- The plasma gasification systems are recognized as more environmentally friendly and can contribute more to the environmental sustainability.
- The plasma gasification process may be as much as 50% more efficient than combustion process, 43% more efficient than pyrolysis process and 19% more efficient than other gasification processes [25].
- It can reduce tar production and achieve a higher carbon conversion rate compared to other gasification methods [26].
- It allows the conversion of the organic wastes into synthesis gas for clean fuel and thermal energy [27].
- The waste metals may easily be recovered by applying plasma gasification process due to high operating temperature while other gasification processes do not have the same capability, because of lower operating temperatures [28].
- Some possibly toxic residues, such as ash, slag, etc. can be easily converted into a glassy material because of high temperature during plasma gasification process [29].
- The slag produced during the plasma gasification can be used as a construction material if required [30],
- The quality of the syngas from plasma gasification system is higher than those of other gasification systems in terms of conversion efficiency of the wastes [31].
- The hydrogen content of the synthesis gas produced during the plasma gasification process is higher than those of other gasification methods [32].
- The exhaust emissions from plasma gasification are much cleaner than those of other gasification methods [25,33].

Considering these important advantages, plasma gasification process can suitably be applied to produce the syngas from coal. During such a plasma coal gasification process, CO and H_2 can be obtained after gas cleaning which is really the ultimate goal of this particular paper. Here, the coal loaded into the plasma gasification unit is gasified at high temperature by means of a plasma torch. The synthesis gas produced in it is passed through the heat exchanger and sent to the gas cleaning unit after being cooled accordingly. Also, the purified gas is pressurized by a compressor, and sent to a hydrogen separation unit, using of the following techniques, such as pressure swing adsorption, cryogenic distillation or membrane separation [34–37]. At the end of the separation process H_2 fuel is obtained. According to the literature results, it can be said that, at the end of the plasma gasification of coal, approximately 0.1–0.17 kg of hydrogen gas is produced from 1 kg of coal [38]. In order to obtain hydrogen from the syngas produced through plasma gasification of coal a correct implementation of one of the hydrogen separation processes is required, as discussed below. Pressure Swing Adsorption (PSA) is known as a batch process in which multiple vessels are used to purge the synthesis gas produced and obtain a constant product gas. In the PSA process, impurities in the synthesis gas at high pressure are largely removed by using adsorbents [39]. In the hydrogen separation process, impurities in the synthesis gas are adsorbed at higher partial pressure and then desorbed at lower partial pressure [37]. The separation process takes place when it comes into contact with the sorbent/solvent in the pressure vessel. The gas with the highest attraction force is trapped, while the others pass through the system. High purity hydrogen is obtained by the PSA method [37]. Cryogenic distillation is another process of separating gases with different boiling points from the gas mixture based on their saturated vapor pressures [37,39–41]. It is then recognized as a separation process taking place by increasing and decreasing of temperature/pressure of the system where the mixing gases are stored [37]. Synthesis gas produced by gasification of coal is sent to the cryogenic distillation unit and decomposed, and after cryogenic separation process high purity hydrogen is obtained [42]. Membranes, that may be thought of as semipermeable barriers for the separation of gases or liquids, enable selective separation [39]. This separation process is carried out by means of the driving force created by the pressure difference, electrical potential difference and temperature difference depending on the type and properties of the membrane used [43]. The separation process of the synthesis gas released as a result of coal gasification is performed with a silica composite membrane or ceramic membrane that can operate at high temperatures and pressures for a long time [44–46].

Due to lack of methodological and systematic evaluations, an up-to-date literature review has been carried out,and a comparative evaluation has been performed to investigate and discuss the hydrogen production from coal gasification. This kind of lack of information has been the main motivation behind the present work. In this study, the paper first discusses the state of the art and conduct a comparative evaluation for better understanding the processess and operating principles, key parameters and outputs available from the systems and their roles in developing more environmentally-benign and sustainable future. Second, a thermodynamic approach for plasma gasification process is presented in order to conduct energy, exergy and exergetic sustainability analyses in terms of the second law of thermodynamics. Third, in order to verify the analysis model by utilizing the literature data taken from various experimental studies, including plasma gasification of coal, a case study is performed. Fourth, the challenges and opportunities of hydrogen production from plasma coal gasification are discussed from various perspectives, in addition to some innovative strategies concerning plasma gasification of coal for hydrogen production developed and suggested in terms of energetic sustainability and environmental sustainability. Fifth, some guiding directions for future on hydrogen production from plasma coal gasification are provided.

In this regard, it is expected that this particular review will contribute to the current literature and provide some help and guidance to the researchers, scientists, engineers, technologists, students, experts, policy makers and investors in terms of the research, design, development, manufacturing, innovation, commercialization, investment, installation, operation, waste management and co-gasification of hydrogen

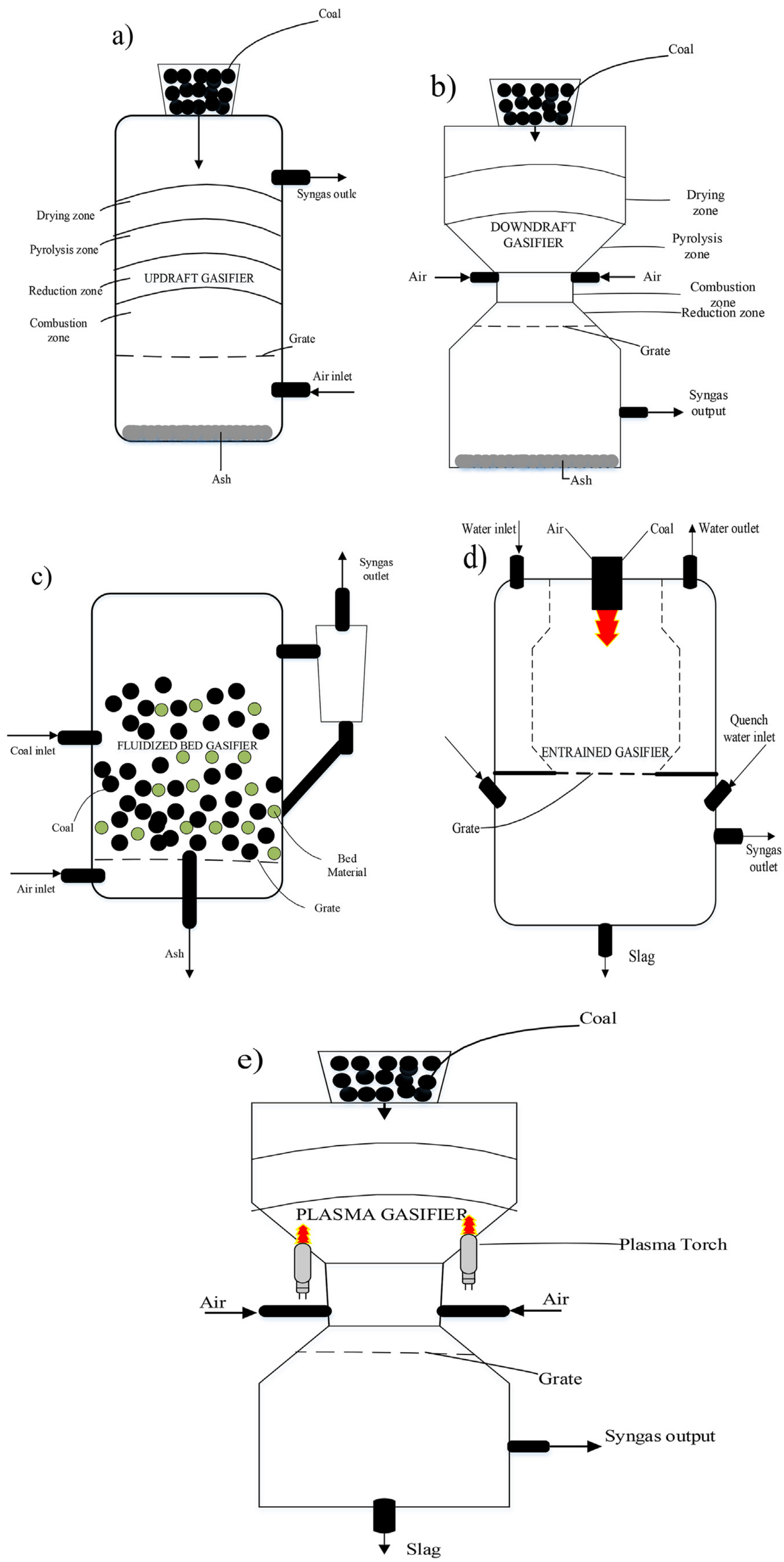

Fig. 1 – Schematic illustrations of gasifier types (a. Updraft Gasifier, b. Downdraft Gasifier, c. Fluidized Bed Gasifier, d. Entrained Gasifier, e. Plasma Gasifier) (Compiled from Refs. [50,56–58]).

production from plasma coal gasification systems for better understanding the effect of clean coal technologies on the environmental sustainability.

State of the art and comparative evaluation

In this section, firstly, the gasifier types and coal gasification processes are comparatively evaluated based on the published literature. Then, the environmental dimensions of coal gasification are discussed, and the hydrogen production cost is compared for various production methods. The review has covered the studies performed between the years of 2000 and 2021 as available in the open literature.

Gasifier types

There are several types of gasification technologies and processes as introduced in the literature. As schematically illustrated in Fig. 1, they are generally classified as fixed bed gasifier, fluidized bed gasifier, entrained bed gasifier and plasma gasifier [11,47,48], and are compared by considering their various parameters as tabulated in Table 1.

Fixed bed gasifiers are divided into updraft gasifier and downdraft gasifier [59,60]. In the updraft gasifier, the fuel is loaded from the upper part of the reactor, and the gasifying agent is supplied to the system from the lower part of the reactor. Synthesis gas produced is taken out from the upper part of the reactor [10,49,50]. In downdraft gasifiers, fuel is loaded from the upper part of the reactor [59–61], and the gasifying agent is sent to the system through the channels opened in the middle of the reactor, and synthesis gas is taken out from the lower part of the reactor [1,10,49,50,62,63].

Fluidized bed gasifiers have many different designs such as bubbling bed, circulating bed, internally circulating bed, spouted bed and dual bed. In these reactors, fuel is loaded into the system from the side of the reactor [10,14,64]. It is quickly mixed with the bed material and heated to bed temperature in a very short time, and gasifying agent is introduced from the lower part of the reactor while the synthesis gas exit takes place from the upper part of the reactor, and the slag exits from the lower part of the reactor [10,14,64,65].

The entrained bed gasifiers used in applications above at least 50 MWth power are fed with fuel, and the gasifying agent is supplied from the top of the reactor [10,66]. While synthesis gas exits from the middle part of the reactor the ash comes out from the bottom part. Residence time is very low, and high temperatures are used to achieve high carbon conversion [1,10,66,67].

Gasification methods of coals

In this section, the published literature has been examined in terms of coal and gasifier types, synthesis gas production quantity, amount of hydrogen production, advantages and disadvantages. In this regard, some important studies are introduced as follows. For example, Messerle et al. [7] presented a plasma technology for processing low-quality brown coal sample, and conducted a thermodynamic evaluation and experimental study. In the experiments, they tried to produce syngas including H_2 by using Turgai brown coal in the amount of 100 kg of coal and 41 kg of water vapor. Long et al. [15] conducted a study on the effect of pressure and fuel feed rate on the degree of gasification of German lignite in the CO_2 rich atmosphere. It was observed that the hydrogen in the synthesis gas produced decreased as the pressure increased. Qiu et al. [24] established a tube type mechanism in order to produce synthesis gas by gasifying coal at atmospheric pressure in steam and air plasma conditions. An optical emission spectroscopy was used for plasma and synthesis gas was analyzed by gas chromatography. They concluded that H_2 and CO contents in the synthesis gas rise with the arc input power increment, and that H_2 content decreases while CO content increases with the coal feed rate increment. Janajreh et al. [68] studied on the plasma gasification and conventional air gasification methods, for the gasification of various raw materials such as coal, car tires, MSW and wood. They pointed out that, that H_2 production rate of plasma gasification is far too much compared to conventional air gasification, and it is much more efficient. Messerle et al. [69] conducted experimental and numerical investigations of plasma gasification of coal with steam and air using the TERRA universal thermodynamic calculation code. They found that the rate of synthesis gas from water vapor gasification of bituminous coal was significantly higher than the synthesis gas obtained from gasification with air, and also contains higher amount of hydrogen. Galvita et al. [70] studied coal gasification in steam and air atmosphere under arc plasma conditions, using Podmoskovnyi brown coal, Kuuchekinski bituminous coal

Table 1 – Comparison of gasifiers.

	CT	SGET	SS	RZT	Scale	CGE	Source
Fixed Bed Gasifier	Lignite Subbituminous	460–650°C	Normal (5 cm)	1000–1100 °C	Large	%80	[10,49,50]
Fluidized Bed Gasifier	Lignite Subbituminous	800–1000 °C	Small (0.6 cm)	800–1000 °C	Large	%78-81	[1,10,49,50]
Entrained Bed Gasifier	All types of coal	900–1600 °C	Very small (0.015 cm)	1990 °C (max)	Large	%80	[10,49–52]
Plasma Gasifier	All types of coal	1250 °C (min)	Normal (5 cm)	1500–5500 °C	Small- Modular	%80-90	[53–55]

CT: Coal Type, SGET: Synthesis Gas Exit Temperature, SS: Sample Size, RZT: Reactor Zone Temperature, Scl: Scale, CGE: Cold Gas Efficiency.

and Canadian petrocoke. They found that, considering the hydrogen production using steam, the most of it comes from Canadian petroleum coke, then from Kuuchekinski bituminous coal, and the least hydrogen production occurred as a result of the gasification of Podmoskovnyi brown coal. Examining the gasification of Kuuchekinski bituminous coal with air instead of steam they also revealed that steam gasification is more advantageous than air gasification in hydrogen production. Smolinski et al. [71] conducted experiments on steam gasification of lignite, hard coal and biomass at a temperature of 700 °C in a laboratory scale fixed bed reactor and compared the results. In the lignite and hard coal gasification tests, they observed that the product gas was mainly composed of hydrogen and carbon dioxide. They observed the highest hydrogen content in the lignite synthesis gas while hydrogen concentration for hard coal and biomass was similar amount. Yoon and Lee [72] carried out microwave plasma gasification of three different types of coal with various O_2/fuel ratios using steam and air as plasma forming gases. They observed that, it is possible to produce synthesis gas with a high H_2 content when pure steam is used as the plasma forming gas. Hong et al. [73] used atmospheric pressure pure vapor torch plasma to gasify Indonesian brown coal and ash contains high amount of moisture. Consequently, it is observed that the hydrogen production rate increases with the coal/steam ratio increment. Shin et al. [74] examined the gasification process of coal using atmospheric pressure pure vapor plasma torch. With this experimental study, they investigated the effects of gas temperature on the molecular fraction properties of the synthesis gas, and maximum hydrogen production rate has been realized at the ratio of 0.55 steam/coal. Uhm et al. [75] gasified the Indonesian brown coals with high ash content by using swirl-type gasifier and two microwave vapor plasma that increase the gas temperature in the reaction chamber for hydrogen-rich synthesis gas production. They achieved complete gasification of the carbons in low-grade coal at 1640 °C in 150 min. Duan et al. [76] conducted the experiments of steam gasification to produce hydrogen-rich gas using high temperature furnace slag. Thermodynamic analysis with Gibbs free energy minimization preformed using the Lagrange multiplier method. In their study, Datong coals were chosen as raw material and, they concluded that increasing the vapor ratio leads to an increase in H_2 concentration, but the extra vapor will consume more energy. Jin et al. [77] conducted experimental studies in autoclaves and supercritical water fluidized bed reactors to obtain supercritical water gasification and sodium dispersion properties of Zhundong coals. They conclude that the synthesis gas resulting from the gasification of the Zhundong coal contains significantly H_2 (average 50%) and CO_2 (average 33%) respectively, and validated the supercritical water fluidized bed reactor appears to be a promising reactor. Xie et al. [78] investigated the chemical cyclic gasification of the Ningdong coals using Fe_2O_3 as an oxygen carrier and obtained gasification properties. They constructed a computational fluid dynamics (CFD) model and analyzed a numerical simulation of gasification processes. Considering the properties of gas flow and gassing, they revealed that their experiments are compatible with the simulation values and also concluded

Table 2 – Comparative evaluation of operational parameters for hydrogen production using fluidized bed gasifier.

FLUIDIZED BED GASIFIER									
Source	Gasifier	Feedstock	Bed Material	Gasification Temperature	Gasifying Agent	Catalyst used	Lab Scale	Pilot Scale	Method/ Software
[15]	Fluidized Bed Gasifier	Lignite	Acid-washed silica sand	850 °C	O_2	–	✓	–	Experimental
[79]	Fluidized Bed Gasifier	Indian coal	–	750–1050 °C	Steam	–	–	–	ASPEN Plus
[81]	Fluidized Bed Gasifier	Bituminous Coal, Meat, Bone Meal	Silica	800–900 °C	Air	✓	✓	–	Experimental
[83]	Fluidized Bed Gasifier	Coal and Dried sewage sludge	Silica sand	810–815 °C	Air	–	✓	–	Experimental
[92]	Fluidized/Fixed Bed Gasifier	Low rank coal char	Quartz sand	700–900 °C	Steam	✓	✓	–	Experimental
[94]	Fluidized Bed Gasifier	Anthracite	Ash	995 °C	Steam, O_2, N_2	✓	–	–	ASPEN Plus
[95]	Fluidized Bed Gasifier	Rice husk-Coal	Sand	900 °C	Air	–	✓	–	Experimental
[96]	Fluidized Bed Gasifier	High ash Indian coals	Ash	950 °C	Air or Steam	–	–	✓	Experimental
[97]	Fluidized Bed Gasifier	Polish hard coal, wood pellet	Olivine	860 °C	Steam	–	✓	–	Experimental
[98]	Fluidized Bed Gasifier	Pine chips Black Coal Sabero Coal	Ash	840–910 °C	Steam-Air	–	–	–	Experimental

Table 3 – Comparative evaluation of hydrogen production by using fluidized bed gasification process.

FLUIDIZED BED GASIFICATION PROCESS											
Source	Gasification type	Feedrate (kg/h)	Gas Product Distribution								LHV
			H_2	CO	CH_4	C_2H_2	C_2H_4	C_2H_6	CO_2	N_2	
[15]	Fluidized Bed Gasification	0.09–0.36	1–12%	20–30%	1-3%	–	–	–	60–70%	–	–
[79]	Fluidized Bed Gasification	15	9–20%	8.5–23%	0.2–8.5%	–	–	–	4.2–6.5%	–	–
[81]	Fluidized Bed Gasification	0.108	21.5–22.7%	29.2–30.6%	–	–	–	–	42.3–45.1%	–	2.3–2.4 MJ/kg
[83]	Fluidized Bed Gasification	0.78	14.64–30.17%	9.46–12.39%	3.77–5.36%	0.001–0.1%	0.01–1.98%	0.001–0.11%	10.64–13.52%	41.42–54.5%	5.13–6.11 MJ/Nm^3
[92]	Fluidized/Fixed Bed Gasification	0.06	52.2–58.4%	12.5–18.6%	2.63–2.71%	–	–	–	26.33–26.35%	–	–
[94]	Fluidized Bed Gasification	20,833	35.43–38.49%	26.35–28.31%	4.89–5.32%	–	–	–	23.60–24.87%	6.07–6.67%	–
[95]	Fluidized Bed Gasification	10.6	8.64%	14%	5.63%	–	–	–	12.38%	–	–
[96]	Fluidized Bed Gasification	15	15–20%	15–20%	1–2%	–	–	–	10–12%	–	–
[97]	Fluidized Bed Gasification	15.4	46%	26%	9%	–	–	–	19%	–	–
[98]	Fluidized Bed Gasification	0.86–1.242	10.47–13.05%	16.16–24.10%	0.92–2.61%	0.13–0.69%	–	–	5.84–8.44%	54.77–63.99%	3.7–5.5 MJ/Nm^3

Table 4 – Comparative evaluation of operational parameters for hydrogen production using fixed bed gasifier.

FIXED BED GASIFIER									
Source	Gasifier	Feedstock	Bed Material	Gasification Temperature	Gasifying Agent	Catalyst used	LS	PS	Method/Software
[9]	Downdraft Fixed Bed Gasifier	Low Rank Coal-Japanese cedar/rice straw/seaweed	–	500–750 °C	Steam	–	✓	–	Experimental
[71]	Fixed Bed Gasifier	Biomass, Lignite and Hard coal	Quartz wool	700 °C	Steam	–	✓	–	Experimental
[82]	Fixed Bed Downdraft Gasifier	Lignite + palm kernel shells	Ash	1000 °C	Air	–	✓	–	Experimental
[85]	Fixed Bed Gasifier	Lignite	quartz wool and quartz sand	600–850 °C	Steam	✓	✓	–	XRD, Raman, FT-IR, and XPS
[101]	Fixed Bed Gasifier	Anthracite and biomass	–	850–1000 °C	Steam	✓	✓	–	Experimental
[102]	Downdraft Fixed Bed Gasifier	Lignite and Sunflower seed cake	–	850 °C	Steam	✓	✓	–	Experimental
[103]	Fixed Bed Gasifier	Low Rank Coal-Biomass	–	800 °C	Steam	–	✓	–	Experimental
[104]	Fixed Bed Downdraft Gasifier	High ash coal-biomass	Silica	690–900	Air	–	–	–	Experimental
[105]	Fixed Bed Gasifier	Polish hard coal and Salix Viminalis	Quartz wool	700–900 °C	Steam	✓	✓	–	Experimental

Table 5 – Comparative evaluation of hydrogen production by using fixed bed gasification process.

FIXED BED GASIFIER								
Source	Gasification type	Feedrate (kg/h)	Gas Product Distribution					LHV
			H_2	CO	CH_4	CO_2	N_2	
[9]	Fixed Bed Downdraft Gasification	0.0005	34.3–52.5%	17.9–27.7%	16.1–20.7%	13.45–17.3%	–	–
[71]	Fixed Bed Gasification	1	57–66%	8–22%	0–4%	18–32%	–	10.9–15.84 MJ/kg
[82]	Fixed Bed Downdraft Gasification	3.5–4.5	2.97–4.29%	3.36–5.82%	1.8–2.52%	4.41–5.6%	–	1.5–2.4 MJ/Nm^3
[85]	Fixed Bed Gasification	3.125×10^{-5}	25.4–35.5%	35.8–39.6%	–	28.6–34.9%	–	–
[101]	Fixed Bed Gasification	0.0006	53.7–70%	20.38–21.15%	0.011–0.02%	6.7–23.9%	–	–
[102]	Downdraft Fixed Bed Gasification	0.005	58–67%	2–6%	1–8%	28–32%	–	–
[103]	Fixed Bed Gasification	0.014	14–51%	2.2–12.7%	0.46–3.25%	3.28–12.58%	–	11.65–12.91 MJ/Nm^3
[104]	Downdraft Fixed Bed Gasification	5.29	7.2–8.2%	6.7–11.2	1.2–1.4%	11.7–15.4%	63.8–73.2%	2.07–2.74 MJ/Nm^3
[105]	Fixed Bed Gasification	0.15	59–67%	6–22%	0–2%	16–31%	–	8.26–11.39 MJ/m^3

Table 6 – Comparative evaluation of operational parameters for hydrogen production using entrained flow gasifier.

ENTRAINED FLOW GASIFIER							
Source	Gasifier	Feedstock	Gasification Temperature	Gasifying Agent	LS	PS	Method/Software
[80]	Entrained Flow Gasifier	Coal, Sawdust, Sewage Sludge, MBM	1300–1500 °C	O_2 and steam	–	–	ChemCAD
[106]	Entrained Flow Gasifier	Bituminous coals and Limestone	1300–1350 °C	O_2	✓	–	Experimental
[107]	Entrained Flow Gasifier	Bituminous coal	1000–1400 °C	CO_2	✓	–	Experimental
[108]	Entrained Flow Gasifier	Pittsburgh #8 seam coal and 28 different coal particle	1790–2249 °C	Steam	–	–	CFD simulation
[109]	Entrained Flow Gasifier	Pulverized coal	1250–1350 °C	Steam and CO_2	–	✓	ASPEN Plus
[110]	Entrained Flow Gasifier	Pulverized coal	1300–1400 °C	Steam or O_2	–	✓	Experimental
[111]	Entrained Flow Gasifier	Black coal	1027–1827 °C	Air	✓	–	Experimental
[112]	Entrained Flow Gasifier	Pulverized coal	827–1827 °C	Air	–	✓	Numerical

Table 7 – Comparative evaluation of hydrogen production by using entrained gasification process.

ENTRAINED GASIFICATION							
Source	Gasification type	Feedrate (kg/h)	Gas Product Distribution				
			H_2	CO	CH_4	CO_2	N_2
[80]	Entrained Gasification	166,100–190,000	12.66–15.55%	26.88–31.86%	0–0.01%	–	–
[106]	Entrained Gasification	40	20.72–30.25%	19.68–28.94%	–	34.64–51.85%	0.78–2.93%
[107]	Entrained Gasification	0.06	1–17%	5–62%	–	10–80%	–
[108]	Entrained Gasification	100,000	27.6–32.9%	54.9–64.89%	4.1–4.45%	0.38–4.46%	0.35–0.76%
[109]	Entrained Gasification	625–1875	25.51–33.30%	51.16–71.7%	–	0.86–6.26%	0.58–12.87%
[110]	Entrained Gasification	1200–1900	25.6–32.5%	56.2–65.1%	–	0.8–6.7%	4.1–6.55%
[111]	Entrained Gasification	83.33	8–12% (Coal M) 5–11% (Coal T)	20–25% (Coal M) 17–19% (Coal T)	–	6–8% (Coal M) 5–8% (Coal T)	–
[112]	Entrained Gasification	8333	10.1–12.1%	20.3–23.3%	0–0.4%	4.7–6.7%	–

that H_2 production increased with the increase in temperature. Paul et al. [79] conducted a simulation study using the Aspen Plus for three different coal types with different ash content up to 48.9%. They determined that the carbon conversion efficiency increases with the increment of temperature and steam to coal ratio.

Co-gasification of coals

In this section, some selected studies have been discussed in terms of coal and organic material types, gasifier types, synthesis gas production quantity, amount of hydrogen production, advantages and disadvantages. Rizkiana et al. [9] performed the gasification process in a fixed bed downdraft reactor by blending low quality coal with three different types of biomass, Japanese cedar, rice straw and seaweed, at relatively low temperatures. They experimentally investigated the effect of different biomass mixing proportions on the coal gasification performance. They observed that the coal gasification rate got better with the increase of biomass proportion in the mixture, and hydrogen production increased with the temperature increment. Maxim et al. [80] carried out the design of a combined cycle power plant based on the gasification of coal and biomass, integrated with carbon capture and storage. They performed an evaluation of hydrogen and electricity generation processes based on carbon capture and storage and gasification of coal and biomass. They carried out four different gasification tests: 100% coal, and 80-20% mixtures of coal-sawdust, coal-sewage sludge, coal-meat and bone meal. The coal-meat and bone meal mixture have the highest hydrogen production potential. Cascarosa et al. [81] evaluated the gasification of low percentages of meat and bone powder (MBM) with coal in a fluidized bed reactor as a potential waste management alternative. They investigated the effect of bed temperature (800–900°C), equivalence ratio (0.25–0.35) and percentage of MBM in solid feed (0–1% by weight) on synthesis gas produced. In the experiment using air as a gasifying agent, they observed that MBM had a very small effect on the synthesis gases H_2, CO and CO_2. They also concluded that the hydrogen concentration increases with temperature while decreasing with equivalence ratio. Thiagarajan et al. [82] examined the thermal behavior and synthesis gas production by mixing palm kernel shells (PKS) and Indian lignite coal (LC) in different proportions. As a result, it was observed that the mixture with 10% coal content had higher flammable gas content, and it has been concluded that increasing the percentage of coal increases hydrogen production. Jeong et al. [83] performed the co-gasification of coal and dried sewage sludge (DSS) using a two-stage gasifier consisting of a fluidized bed gasifier and a tar crushing reactor. They investigated the effect of coal and DSS mixing ratio. They found that the synthesis gases obtained from the tar crushing reactor filled with activated carbon contained a high percentage of hydrogen (27.7%). They observed that upon gasification of coal/DSS mixtures, the hydrogen content decreases and the tar content increased with the increment of DSS percentage in the mixture. Gasification of 70% DSS mixture was observed to increase the yield of condensed tar by only 0.1% by weight compared to coal gasification. Finally, a hot filter filled with Fe-impregnated activated carbon was applied to completely remove tar from the generating gas, resulting in the production of tar-free and hydrogen-rich gas (30% by volume).

Utilization of catalysts in coal gasification

In this section, some key issues on the use of catalysts in the gasification of coal such as coal and catalysts types, gasifier types, synthesis gas production quantity, amount of hydrogen production, advantages and disadvantages are discussed in detail. Cheng et al. [84] investigated how the supercritical water gasification method becomes an efficient gasification method for semicoke. They systematically examined the effects of alkaline catalysts (K_2CO_3, KOH, Na_2CO_3 and NaOH). They concluded that the hydrogen yield increases with alkaline catalyst addition, increasing temperature, catalyst load increment, decreasing feedstock concentration and proper flow rate of preheated water. Li et al. [85] experimentally studied the catalytic effect of calcium during steam gasification by adding calcium to ashes obtained from Shengli coals. It has been observed that calcium has a significant supportive effect in vapor gasification of ash samples by decreasing the activation energy. The use of Ca-based catalysts is one of the most effective methods used not only for coal but also for biomass and sludge gasification [86–91]. Qiu et al. [92] performed the gasification process of Na-Char, Ca-Char and a Na/Ca-Char mixture with different partial vapor pressures using a micro fluidized bed reaction analyzer in the temperature

Table 8 – Comparative evaluation of operational parameters for hydrogen production using plasma gasifier.

PLASMA GASIFIER

Source	Gasifier	Feedstock	Gasification Temperature	Gasifying Agent	Catalyst used	Lab Scale	Pilot Scale	Method/Software
[7]	Plasma Gasifier	Low Rank Brown Coal	27–5727 °C	Steam	–	–	–	TERRA
[24]	Arc Plasma Gasifier	Bituminous coal	–	Steam/Air	–	✓	–	Experimental
[68]	Plasma Gasifier	RTC Coal	968 °C	Air/Steam	–	–	–	Lagrange multiplier method-Aspen Plus
[69]	Plasma Gasifier	Bituminous Coal	27–5727 °C	Steam and Air	–	✓	–	TERRA
[70]	DC Plasma Gasifier	Podmoskovnyi brown coal, Kuuchekinski bituminous coal and Canadian petrocoke	750 °C	Steam/Air	✓	✓	–	Experimental
[72]	Microwave Plasma Gasifier	Shenhua Coal, Indonesian coal Charcoal	–	Air and Steam	–	✓	–	Experimental
[73]	Microwave Plasma Gasifier	Brown Coal	5727 °C	Air/Steam	–	✓	–	Experimental
[74]	Microwave Plasma Gasifier	Shenhua Coal	5727 °C	Steam	–	✓	–	Experimental
[75]	Microwave Steam Plasma Gasifier	Brown Coal	1640 °C	Steam	–	✓	–	Experimental
[113]	Plasma Gasifier	Kuuchekinski bituminous coal Canadian petrocoke (CP)	1527–3727 °C	Steam	–	–	–	TERRA

Table 9 – Comparative evaluation of hydrogen production by using plasma gasification process.

PLASMA GASIFICATION

Source	Gasification type	Feedrate (kg/h)	H_2	CO	CH_4	CO_2	N_2	LHV
[7]	Plasma Gasification	7.4	46.8–51%	39.3–46%	–	–	4.9–9.9%	13 MJ/kg
[24]	Arc Plasma Gasification	3	35–45%	32–37%	–	2.3–2.6%	–	–
[68]	Plasma Gasification	3600	50.28%	40.89%	0.01%	0.05%	7.83%	15.94 MJ/kg
[69]	Plasma Gasification	4–4.7	16.6–61.2%	21.5–45.8%	–	–	2.7–49.4%	–
[70]	DC Plasma Gasification	2.5-100	18.2–57.4%	34.1–41.5%	–	–	2.7–43.7%	–
[72]	Microwave Plasma Gasification	1.26	22–63%	17–45%	0.5–4%	16–33%	–	8.22–11.2 MJ/Nm^3
[73]	Microwave Plasma Gasification	2.2	36–49%	13–24%	3–4%	24–46%	–	–
[74]	Microwave Plasma Gasification	2.2	29–52%	16–22%	2–4%	25–52%	–	–
[75]	Microwave Steam Plasma Gasification	90	39.8%	32%	–	18.2%	9.7%	–
[113]	Plasma Gasification	KBC:4 CP: 2.5	KBC:55.8% CP: 63.1%	KBC:41.5% CP:36.2%	–	–	KBC:2.7% CP:0.7%	–

Table 10 – Comparative evaluation of operational parameters for hydrogen production using other type gasifiers.

OTHER TYPE GASIFIERS								
Source	Gasifier	Feedstock	Gasification Temperature	Gasifying Agent	Catalyst used	Lab Scale	Pilot Scale	Method/Software
[78]	Fuel Reactor	Ningdong Coal	850–950 °C	Water vapor	✓	–	–	ANSYS FLUENT
[93]	Chemical Looping Gasification	Coal	750 °C	O_2	✓	–	–	Thermodynamic Analysis
[99]	Horizontally Placed Boat Reactor	Lignite char	750–850 °C	Steam	✓	–	–	Experimental
[100]	High Pressure Reactor	Bituminous coal	800–1000 °C	Steam	✓	✓	–	Experimental
[114]	Gasifying Reactor	Olive pomace, Coal and Petcoke	900 °C	Steam	✓	✓	–	Experimental
[115]	Spout-Fluid Bed Gasifier	High Ash Chinese Bituminous Coal	950–980 °C	Air and Steam	–	–	✓	Experimental

Table 11 – Comparative evaluation of hydrogen production by using other type gasification processes.

OTHER TYPE GASIFICATION PROCESSES								
Source	Gasification type	Feedrate (kg/h)	H_2	CO	CH_4	CO_2	N_2	LHV
[78]	Gasifying Reactor	43.1	45.5–48.67%	21.33–23.22%	1.22–5.5%	13.05–15.79%	–	–
[93]	Chemical Looping Gasification	100	53.15%	10.88%	10.85%	25.11%	–	–
[99]	Horizontally Placed Boat Reactor	0.0001	62.1%	13.4%	2.23%	22.33%	–	–
[100]	Gasifying Reactor	24×10^{-5}	54–57%	42.6–45.7	–	–	–	–
[114]	Thermogravimetric Analysis	20×10^{-6}	1.01–9.38%	0.26–3.65	63.7–68.7%	23.23–30.04%	–	–
[115]	Spout-Fluid Bed Gasification	317–330	14.36–16.54%	10.55–11.68%	1.75–2.91%	12.75–13.96%	54.54–56.95%	4.18–4.74 MJ/Nm^3

range of 700–900 °C. They concluded that using Na and Ca catalysts, unlike non-catalytic gasification, can accelerate the rate of gas release during gasification and even significantly increase H_2 production, and observed that the increase in catalyst activity with increasing temperature increases the H_2 production. Jiang et al. [99] investigated the steam gasification of coal char using a Na/Fe bimetallic catalyst. They observed that the bimetallic catalyst with a suitable loading showed a higher activity at 700–800 °C to accelerate the gasification rate than the Na or Fe monometallic catalysts. They concluded that compared to sodium catalyst, the bimetallic catalyst is conducive to a higher H_2 production by reactions with steam. Spiewak et al. [100] aimed to evaluate the efficiency of impregnation of K, Na and Ca based catalysts onto a coal surface and the effect of these catalysts on steam gasification reactions of coals. They concluded that the addition of a catalyst or an increase in temperature, regardless of its type and amount, generally results in an increase in the rate of formation of the main gas components, namely CO and H_2. With the decrease in the process time H_2 production rate increases.

A comparative evaluation of operating parameters and synthesis gas production of different type gasifiers (fluidized bed, fixed bed, entrained flow, plasma and other type gasifiers) is further performed in this section. The data obtained as a result of the detailed literature review are given in Tables 2–11.

When looking at the comparative evaluations of operational parameters for hydrogen production using fluidized bed gasifier, it is observed that the gasification temperature varies between 700 and 1400 °C. Considering the studies conducted, it is further observed that subbituminous coal, bituminous coal, low rank coal, lignite, semicoke and anthracite were used as feedstock. In the studies, it was seen that ash, silica sand, quartz sand and silica were used as bedding material. Air, steam, supercritical water, O_2 and N_2 are used as gasifying agents. Generally, K, Na, Fe and Ca are used as catalysts. ASPEN Plus or CEA Simulation was used in the simulation studies. Gasification of coal with a fluidized bed gasifier is generally lab scale. A comparative evaluation of hydrogen production using the fluidized bed gasification process is given in Table 3. The amounts of feedstock used vary between 0.8 and 20833 kg/h. The amount of H_2 released as a result of gasification is 4.5–59%, the amount of CO is 2–43%, the amount of CH_4 is 0.92–21.26%, the amount of C_2H_2 is 0.001–0.69%, the amount of C_2H_4 It was observed that the amount of C_2H_6 ranged from 0.001 to 0.11%, the amount of CO_2 was 4.2–45.1% and the amount of N_2 was 6.07–63.99%. LHV values of syngas released as a result of gasification of coal with fluidized bed gasifier is in the range of 2–6.11 MJ/Nm^3.

Upon close comparative evaluation of operational parameters for hydrogen production using fixed bed gasifier, it is seen that the gasification temperature varies between 500 and 1000 °C. Gasification of coal with a fixed bed gasifier is generally lab scale. Comparative evaluation of hydrogen production using the fixed bed gasification process is given in Table 5. The amount of feedstock used varies between 1 g between 4.5 kg/h. The amount of H_2 released as a result of gasification is 2.97–67% and 1–192 mmol/g, the amount of CO is 2–23.9% and 1–75 mmol/g, the amount of CH_4 is 1–4.6% and 2.7–4.5 mmol/g, the amount of CO_2 was 4.41–33.7% and 0.8–85 mmol/g and the amount of N_2 was 63.8–73.2%. LHV values of syngas released as a result of gasification of coal with fixed bed gasifier is in the range of 1.5–15.84 MJ/Nm^3.

Considering the comparative evaluation of operational parameters for hydrogen production using entrained flow gasifier, it is noted that the gasification temperature varies between 827 and 2249 °C. With the studies conducted, it is further noted that subbituminous coal, bituminous coal, pulverized coal, low rank coal and lignite were used as feedstock. Oxygen, carbon dioxide and steam are used as gasifying agents. The use of catalysts was not observed in the coal gasification studies carried out with the entrained flow gasifier. Although the gasification of coal with the entrained flow gasifier is generally carried out at lab scale, there is a pilot scale gasification study in the literature. Comparative evaluation of hydrogen production using the entrained gasification process is given in Table 7. The amount of feedstock used varies between 3.6 and 190,000 kg/h. The amount of H_2 released as a result of gasification is 1–32.5%, the amount of CO is 5–65.1%, the amount of CH_4 is 0–0.01%, the amount of CO_2 was 0.8–80% and the amount of N_2 was 0.78–6.55%.

After conducting the comparative evaluation of operational parameters for hydrogen production using plasma gasifier, it is found that the gasification temperature varies between 1023 and 6000 K. Oxygen, air and steam are used as gasifying agents. In the coal gasification studies carried out in plasma gasifiers, the number of studies using catalysts is limited. Note that some powerful software packages, such as ASPEN Plus, ANSYS Fluent and TERRA, were used in the simulation studies. Gasification of coal with such a plasma gasifier has generally been carried out on laboratory scale. A comparative evaluation of hydrogen production using the plasma gasification process is given in Table 9. The amount of feedstock used varies between 1.26 and 3600 kg/h. The amount of H_2 released as a result of gasification is 16.6–63%, the amount of CO is 16–46%, the amount of CH_4 is 0–4%, the amount of CO_2 was 0.05–52%.

After studying the operational parameters comparatively for hydrogen production using some other types of gasifiers, it is noticed that the gasification temperature varies between 750 and 1000 °C. Oxygen, air and steam are used as gasifying agents. Generally, K, Na, Fe and Ca are used as catalysts. The ANSYS Fluent and thermodynamic analysis as a method were used in the simulation studies. Although the gasification of coal with different types of gasifiers is generally carried out at lab scale, pilot scale gasification study is available in the literature. Comparative evaluation of hydrogen production using other type gasification processes are given in Table 11. The amount of feedstock used varies between 0.2 g and 330 kg/h. The amount of H_2 released as a result of gasification is 1–62.36%, the amount of CO is 10.55–32.5%, the amount of CH_4 is 1–5.5%, the amount of CO_2 was 12.75–15.79% and the amount of N_2 was 54.54–56.95%. LHV value of syngas released as a result of gasification of coal with different type gasifiers are in the range of 4.18–4.74 MJ/Nm^3.

The studies carried out using different gasifiers as a result of the literature search conducted by examining the

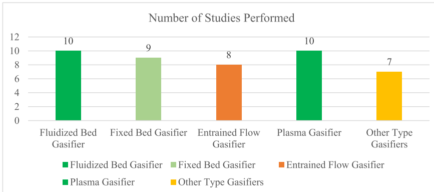

Fig. 2 – Number of research articles analyzed in this paper.

studies conducted between the years of 2000–2021 are shown in Fig. 2.

Environmental dimension of hydrogen production from coal

Coal gasification process has recently been preferred, over conventional combustion practices, to be a popular practice due to the reduced environmental impact and increased process efficiency for hydrogen production. Searching the environmental performance of gasification studies is necessary to show that the system is a sustainable and clean system. Considering the studies conducted in recent years, gasification of coal with lab scale, industrial or commercial processes is a cleaner and more sustainable practice against human health and the environment compared to energy production with conventional systems. The harmful substances released into the environment in conventional combustion processes are reduced to very low amounts with the coal gasification process. In addition, the amount of solid waste generated as a result of gasification is very low compared to incineration [116]. Compared to conventional methods, coal gasification process has a positive effect on human life and nature by reducing air pollution. After the coal gasification process, the products (tar, NOx, SOx, dioxins, furans, hydrocarbons and CO) leaving the reactor should be checked before discharging into ambient air [116,117]. Solid wastes released after the coal gasification process can be used as fertilizers in industry or stored in landfills. Some coal gasification studies are listed in Table 12 to further evaluate their environmental impact by taking into consideration the gasifier type, feedstock, solid waste (char, tar, ash) from the gasifier, CH_4 and CO_2 amounts contained in the syngas. In addition, the global warming potentials (GWPs) of the gasifiers are calculated, depending on the CO_2 and CH_4 emissions. It is generally known that the GWP value is 1 for CO_2, and, for other gases, it varies depending on the gas and time period. For example, the GWP value for CH_4 is 25.

The effect of any system on global warming is generally determined by considering the carbon dioxide equivalent of the released gases. When the GWP values calculated according to the amount of CO_2 as gasification exhaust gas are examined, it can be understood whether or not the gasifier is the cleanest and environmentally friendly. Liu et al. [123] found that the emission value of the gas released from the gasification of coal with biomass is lower than the emission

Table 12 – Global warming potential evaluation of hydrogen production from coal.

Source	Reactor	Feedstock	Feedrate (kg/h)	Syngas flow (Nm^3/kg)	CO_2 (m^3/kg_{syngas})	GWP (kg_{CO2}/kg_{fuel})
[24]	Plasma reactor	Bituminous coal	3	–	0.1	0.092
[71]	Fixed Bed Reactor	Lignite, Hard coal	1	1.6–2.2	0.368–0.418	0.411–0.467
[73]	Microwave plasma reactor	Brown Coal	2.2	–	0.746	0.686
[74]	Microwave plasma reactor	Brown Coal	2.2	–	0.746	0.686
[75]	Microwave Steam Plasma Gasification	Brown Coal	90	–	0.853	0.7849
[78]	Gasification reactor	Coal: 11.2 kg/h Wood: 6.2 kg/h	17.4	1.72	0.337	0.31
[81]	Fluidized Bed Gasification	Bituminous coal-MBM	0.108	3.3	1.3959–1.4883	1.56–1.664
[84]	Supercritical water gasification	Semicoke	–	–	0.622–2.104	0.572–1.936
[95]	Bubbling Fluidized Bed Gasification	Rice husk-Coal	8.1–10.6	2.3–4.5	0.224–0.542	0.2241–0.541
[97]	Fluidized Bed Gasification	Polish hard coal-wood pellets	15.4	1.396	0.265	0.296
[98]	Fluidized Bed Gasifier	Black Coal Pine chips Sabero coal	0.61–1.24	1.89–2.46	0.11–0.21	0.123–0.231
[102]	Downdraft Fixed Bed Gasifier	Lignite	0.005	–	2.056	1.892
[115]	Spout-Fluid Bed Gasifier	High Ash Chinese Bituminous Coal	330	2.53	0.353	0.394
[118]	AC Plasma Gasifier	Coal	–	3.41	0.253	0.233
[119]	Fixed bed reactor	Mengdong Coal	0.006	–	0.335–0.43	0.308–0.396
[120]	Supercritical water gasification	Zhundong coal	–	–	1.05	0.968
[121]	Supercritical water gasification	Lignite Bituminous coal	–	–	0.717–1.91	0.66–1.76
[122]	Fluidized bed reactor	Yalloum Coal	–	–	0.157–1.05	0.01452–0.968

value of the gas released from coal gasification. In the table here, the GWP value calculated as a result of cogasification with biomass is relatively lower than the GWP value calculated as a result of gasification only of coal.

Economic dimensions of hydrogen production from different methods

There are many potential hydrogen production methods as discussed in the literature. Some of the hydrogen production methods are carried out using renewable energy sources. The operating and maintenance costs of steam-methane reforming, solar, wind, hydropower electrolyser, nuclear and coal gasification methods used in hydrogen production and hydrogen production cost per kg are given in Table 13.

Analysis: thermodynamic approach

In this work, coal gasification processes for hydrogen production have been compiled by considering the recently published studies in the literature. Various aspects of these processes have been comparatively evaluated. For better understanding the thermodynamic aspects of the coal gasification for hydrogen production, among the processes, the plasma-based coal gasification is selected. In this regard, a case study is also performed in terms of thermodynamic analysis.

Plasma coal gasification system

A schematic illustration of the plasma coal gasification process is shown in Fig. 3. This process is summarized below.

The inner surface of the gasifier where plasma gasification takes place is covered with ceramic material. The plasma coal gasification process was carried out with the help of a DC plasma torch. In the plasma gasification process, air and steam are used as gasifying agents [132]. Air, which is at room conditions is pressurized with the help of a compressor and sent to the plasma gasifier. Steam, the other gasifying agent, is obtained by the conversion of ambient water into the steam generator and into steam. Steam produced has a temperature higher than 250 °C [70,115]. The steam produced in the steam generator is sent to the gasifier. Coal used as feedstock material is loaded into the system from the upper part of the gasifier near the torch. Plasma gasification process takes place at high temperatures [133]. After plasma gasification, raw syngas is released and a very small amount of slag output is observed. Hydrogen fuel is obtained by passing the produced raw syngas through several different processes. To obtain pure hydrogen, the first step after the plasma gasification unit is to cool the raw syngas. Raw syngas is cooled with the help of a heat exchanger using water. Water passing through the heat exchanger turns into steam form. Generally, this non-radioactive vapor is thrown into the atmosphere. Raw syngas leaving the heat exchanger is sent to the cleaning unit. In the cleaning unit, the syngas is separated from the particles and ashes it contains. The clean syngas from the cleaning unit

Table 13 – Cost comparison of different hydrogen production methods.

Hydrogen Production Method	Capital Cost	Source	Hydrogen Production Cost	Source
Steam Reforming	3.4 M$	[124]	2.42 $/kg	[124]
	150 M$	[125]	17 cent/Nm^3-H_2	[126]
Solar PV	12–54.5 M$	[127]	3.5–23.27 $/kg	[124,127–129]
	399.6 M$	[128]		
Wind	0.045 M$ (24 MW)	[124]	5.1–6.46 $/kg	[129]
	335.9	[125]		
Electrolyser	250–1100 EUR/(Nm^3/h)	[130]	8 $//kg-$H_2$	[131]
			32-65 cent/Nm^3-H_2	[126]
Nuclear	39.6–2107.6 M$	[129]	4.15 $/kg	[129]
			2.17–7 $/kg	[127]
Coal Gasification	435.9 M$	[127]	25 cent/Nm^3-H_2	[126]
	507.3 M$	[125]		

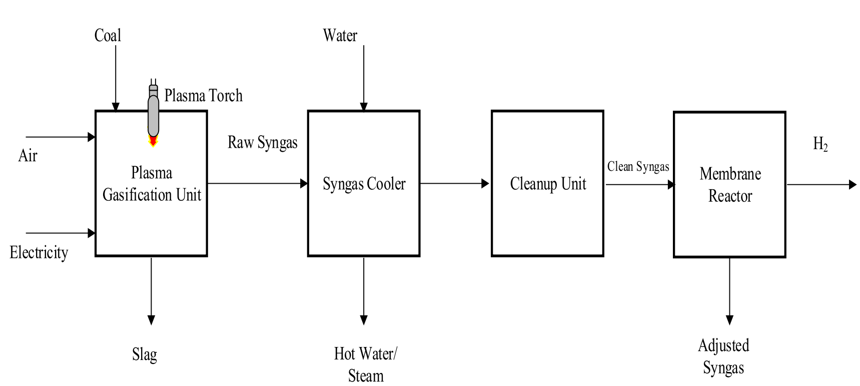

Fig. 3 – Schematic illustration of plasma coal gasification process (compiled from Ref. [14]).

is sent to the membrane reactor. Selective separation is provided with the help of membranes, which are also considered as semi-permeable barriers to separate gases [39]. The separation process is carried out by the driving force created by the pressure difference, electrical potential difference and temperature difference depending on the type and properties of the membrane used [134]. The separation process of the synthesis gas released as a result of the gasification of coal is performed with a silica composite membrane or a ceramic membrane. Thus, pure hydrogen used in fuel cells, transportation vehicles and many other areas is obtained [135,136].

While performing the experimental processes described above, the values of the parameters such as flow rate, temperature and current are measured with the external or internal equipment used. Temperature measurement is in two ways. The first is to measure the surface temperature in the cross section of the reactor, the second is to measure the high temperature inside the reactor. Infrared thermometers are used to measure the surface temperature in the cross section of the reactor [7]. Pyrometers are used for high temperature measurement inside the reactor [69]. Additional holes are drilled in the plasma gasification reactor to connect pyrometric equipment and measure temperatures in the reaction zone. Correct measurements made through these holes are up to 3273 K with a maximum error of 1% [7]. A multimeter and clamp meter are used to measure the current of the plasma torch. The current passing through the electric cable coming to the plasma torch is measured by using a clamp meter. With the multimeter, measurements are made over the poles. A flow meter is used to use the amount of gasifying agent to be sent to the system. With flowmeters, appropriate experimental conditions are adjusted by increasing or decreasing the air flow. A gas analyzer and gas chromatography are used to analyze the components of the synthesis gas produced after the plasma coal gasification process [24,75]. The plasma coal gasification process is shown schematically above. Afterwards, it is explained how hydrogen production takes place and which equipment is used for measurements. Table 14 contains the main parameters of the plasma coal gasification system while hydrogen production is carried out.

Assumptions

In order to perform analysis and assessment, the following assumptions are made:

- A steady state steady flow process takes place in the system [107].
- The changes in kinetic and potential energies are neglected [148].
- The residence time is not taken into account [76].
- Both air and steam are selected to be gasifying agents.
- The uniform temperature and pressure are assumed in the reactor [138].
- The heat loss from the reactor surface and other parts of the system are considered.
- The chemical exergy values of the coals are estimated using the methodology in the literature [149].
- The values of all thermodynamic properties as well as specific chemical exergy are taken from the literature [149,150].
- After the plasma gasification process, the main outputs include heat, H_2, N_2, CO, CO_2, CH_4 and slag.
- The syngas containing hydrogen and carbon monoxide are two useful outputs from the system. However, the wastes from the system include the heat, CO_2, N_2, CH_4 and slag.

An exergetic sustainability analysis of the plasma gasification system is performed in the case study section by taking into consideration the above listed assumptions.

Table 14 – Main parameters of plasma coal gasification.

Parameters	Content	Source
Agents	Air, O_2, Steam, Ar, N_2	[15,79,84,103,137]
Equivalence ratio	<0.32	[115,138]
Operating Temperature	>1400 K	[24,70,113,139]
Feedstock Type	Lignite, Bituminous coal, Subbituminous coal	[1,10,49–52]
Gasification Speed	Variable	[140]
Start-Up Time	Variable	[140]
Catalyst	Na_2CO_3, K_2CO_3, Li_2CO_3	[77,81,85,105,114]
Feedstock Particle Size	0.05–5 cm	[1,10,49,50]
Feedstock Rate	Variable	–
Bed Material	Quartz, Wool, Sand	[83,85,92]
Steam/Fuel Ratio	Variable	[141]
Air/Fuel Ratio	Variable	[141]
Feedstock Calorific Value	16,000–40,000 kJ/kg	–
Plasma Energy Rate	Variable	[141]
Operation time	Variable	[140]
Total operating time	Variable	[140]
Plasma energy ratio	Variable	[144]
Cold gas efficiency	<89%	[142]
Hot gas efficiency	95%	[143,144]
Ash rate	Variable	[145]
Fuel consumption rate	Variable	[140–146]
Specific gasification rate	Variable	[147]
Thermal efficiency/Gasification efficiency	<57%	[10,77,85,114]

Mass balance equation.

Considering the assumptions, the general mass balance equation can be written as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

The mass balance equation including each component can be written as below,

$$\dot{m}_{Coal} + \dot{m}_{air} + \dot{m}_{steam} = \dot{m}_{CO} + \dot{m}_{H_2} + \dot{m}_{N_2} + \dot{m}_{CO_2} + \dot{m}_{slag} \tag{2}$$

Energy balance equation.

Considering the assumptions, the general energy balance equation can be written as

$$\sum \dot{E}_i = \sum \dot{E}_o \tag{3}$$

$$\begin{aligned}\dot{m}_{Coal}LHV_{Coal} + \dot{m}_{air}h_{air} + \dot{m}_{steam}h_{steam} + \dot{W}_{torch} \\ = \dot{m}_{CO}\,(\,LHV_{CO}) + \dot{m}_{CO}(h_{CO} - h_{o_{CO}}) + \dot{m}_{H_2}(LHV_{H_2}) \\ + \dot{m}_{H_2}\left(h_{H_2} - h_{o_{H_2}}\right) + \dot{m}_{N_2}\left(h_{N_2} - h_{o_{N_2}}\right) + \dot{m}_{CO_2}\left(h_{CO_2} - h_{o_{CO_2}}\right) \\ + \dot{Q}_{loss}\end{aligned} \tag{4}$$

Exergy balance equation.

Considering the assumptions, the general exergy balance equation can be written as

$$\sum \dot{E}x_i = \sum \dot{E}x_o + \dot{E}x_{loss} \tag{5}$$

$$\begin{aligned}\dot{E}x_{dest} = \Big[\dot{m}_{Coal}ex^{ch}_{Coal} + \dot{m}_{air}\left((h_{air} - h_{o_{air}}) - T_0(s_{air} - s_{o_{air}})\right) \\ + \dot{m}_{steam}\left((h_{steam} - h_{o_{steam}}) - T_0(s_{steam} - s_{o_{steam}})\right) + \dot{W}_{torch}\Big] \\ - \Big[\dot{m}_{CO}\left((h_{CO} - h_{o_{CO}}) - T_0(s_{CO} - s_{o_{CO}})\right) + \dot{m}_{CO}\,ex^{ch}_{CO} \\ + \dot{m}_{H_2}\left(\left(h_{H_2} - h_{o_{H_2}}\right) - T_0\left(s_{H_2} - s_{o_{H_2}}\right)\right) + \dot{m}_{H_2}ex^{ch}_{H_2} \\ + \dot{m}_{N_2}\left(\left(h_{N_2} - h_{o_{N_2}}\right) - T_0\left(s_{N_2} - s_{o_{N_2}}\right)\right) + \dot{m}_{N_2}ex^{ch}_{N_2} \\ + \dot{m}_{CO_2}\left(\left(h_{CO_2} - h_{o_{CO_2}}\right) - T_0\left(s_{CO_2} - s_{o_{CO_2}}\right)\right) \\ + \dot{m}_{CO_2}ex^{ch}_{CO_2} + \dot{Q}_{loss}\left(1 - \frac{T_0}{T}\right)\Big]\end{aligned} \tag{6}$$

Energy efficiency

$$\eta_{en} = \frac{\dot{m}_{H_2}(HHV_{H_2}) + \dot{m}_{H_2}(h_{H_2} - h_{0H_2}) + \dot{m}_{CO}(HHV_{CO}) + \dot{m}_{CO}(h_{CO} - h_{0CO})}{\sum \dot{E}_{in}} \tag{7}$$

Exergy efficiency

$$\eta_{ex} = \frac{\dot{E}x_{out_{CO}} + \dot{E}x_{out_{H_2}}}{\sum \dot{E}x_{in}} \tag{8}$$

Exergetic efficiency of hydrogen production

$$\eta_{ex_{H_2}} = \frac{\dot{E}x_{out_{H_2}}}{\sum \dot{E}x_{in}} \tag{9}$$

Exergetic efficiency of syngas production

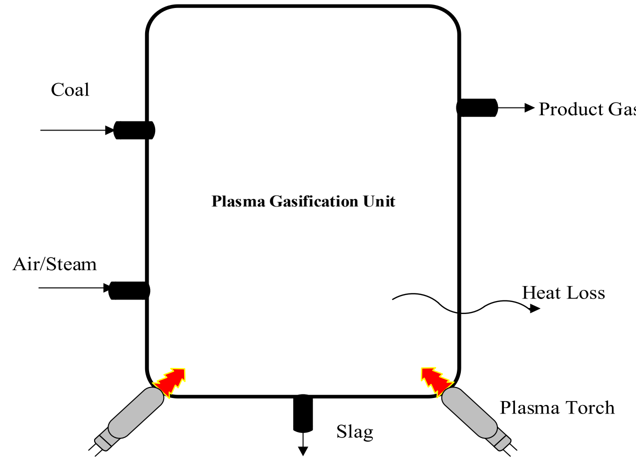

Fig. 4 – Schematic illustration of a plasma coal gasification unit.

$$\eta_{ex_{syngas}} = \frac{\sum \dot{E}x_{outsyngas}}{\sum \dot{E}x_{in}} \tag{10}$$

Waste exergy ratio [151–154].

$$r_{wex} = \frac{\sum \dot{E}x^{Q}_{out} + \sum \dot{E}x_{loss}}{\sum \dot{E}x_{in}} \tag{11}$$

Exergy recoverability ratio [151–154].

$$r_{exr} = \frac{\sum \dot{E}x_r}{\sum \dot{E}x_{in}} \tag{12}$$

Exergy destruction ratio [151–154].

$$r_{exd} = \frac{\sum \dot{E}x_{dest}}{\sum \dot{E}x_{in}} \tag{13}$$

Environmental impact factor [151–154].

$$f_{envi} = r_{wex} \times \left(\frac{1}{\eta_{ex}}\right) \tag{14}$$

Exergetic sustainability index [151–154].

$$\Theta_{esi} = \frac{1}{f_{envi}} \tag{15}$$

Analysis: case study

In this section, a case study on the plasma coal gasification process has been conducted. For this purpose, firstly the required data have been taken from the literature [24,68–70,72] and then energy and exergy analyses (Eqs. (1)–(15)) have been achieved for the system shown in Fig. 4.

The results of exergetic sustainability analysis are listed in Table 15.

When the values listed in Table 15 are evaluated and discussed, in terms of exergy efficiency, syngas production efficiency, waste exergy ratio, exergy destruction ratio, environmental impact factor and exergetic sustainability index, the best results are obtained for the study conducted by Messerle et al. [69]. On the other hand, in terms of energy efficiency, the best result is obtained from the study conducted by Yoon and Lee [72]. In terms of thehydrogen production efficiency, the best result is obtained from the study carried out by Galvita et al. [70]. In terms of exergy recoverability ratio, the best result is obtained from the study performed by Qiu et al. [24].

Challenges

When the studies in the literature are examined, many difficulties have been encountered in the process from gasification of coal to hydrogen production. Eliminating these difficulties will not only increase confidence in coal gasification technologies, but also eliminate some question marks in mind. To summarize the main problems encountered; The need for more efficient use of the heat released in the gasifier, hot gas cleaning, lack of standards in coal gasification, initial investment cost and the return on this investment, technical risks and skepticism about environmental risk [155]. For example; hot gases need to be cooled as they exit the reactor. This cooling process is done using heat exchangers. The heat generated as a result of the process is very valuable. This heat can be used for many purposes, including electricity generation, and heating. However, using heat exchangers to cool hot gas above 1400 °C has engineering challenges depending on temperature and material [27,155]. Another challenge is the lack of a specific national or international standard on coal gasification. Lack of standards in coal gasification makes project development difficult. Project developers' discussions on coal gasification generally focus on efficiency, economic performance and economic risk. The biggest obstacle to the use of wider coal gasification for electricity generation is the economy, especially the cost of capital [156–158]. Lack of data in studies on coal gasification, limited number of prototypes, and lack of safety regulations in countries may cause people to doubt the environmental impact of this technology. Especially, the synthesis gas produced at a pressure close to atmospheric pressure causes concerns about the reliability of gas collection systems [159]. Thought of how long these facilities will pay for themselves as much as the initial investment cost makes investors who want to direct this area think. It is predicted that coal gasifiers will be more efficient, safer, more reliable and more preferred systems if the above mentioned difficulties are reduced or completely eliminated. The fact that the systems are more efficient and preferred will also eliminate the economic concerns of the investors.

The challenges encountered during the coal gasification process may be summarized below.

- As a result of coal gasification, syngas with a high carbon footprint is released [132]. The carbon content of the syngas should be reduced by improving system construction and operating conditions of the process.
- Due to the sulfur contained in coal, sulfur oxides can be produced during gasification, which causes polluting acid rain [132]. Therefore, in order to reduce the environmental pollution of the gasification process of the coal, the sulfur reduction system should be added to the system.
- Different devolatilization temperatures coupled with segregation of coal and other type fuels can reduce the volatilization of coal [132].
- Condensation occurring during coal gasification process causes tars, and ash in gasification fuel causes sintering and corrosion of the gasifier building metal [132].
- Differences in density, shape and size of coal and other fuel particles to be co-gasified may have a negative effect during gasification [132]. Therefore, the appropriate gasifier should be selected for coal gasification.

Table 15 – Thermodynamic analysis results for the case studies.

Source	Messerle et al. [69]	Yoon and Lee [72]	Galvita et al. [70]	Qiu et al. [24]
Feedrate (kg/h)	4	1.26	6.7	3
Gasifier type	Plasma gasifier	Plasma gasifier	Plasma gasifier	Plasma gasifier
Coal type	Bituminous coal	Shenhua coal	Podmoskovnyi coal	Bituminous coal
Gasifying agent	Air	Steam and Air	Steam and N_2	Steam and Air
Work type	Simulation and Experimental	Experimental	Experimental	Experimental
Present study evaluates these systems as below				
Exergy inlet (kW)	38.389	15.197	95.727	83.751
Exergy outlet (kW)	31.426	11.453	71.675	58.743
Exergy loss	6.977	3.743	24.053	25.008
Energy efficiency	0.471	0.512	0.404	0.285
Exergy efficiency	0.342	0.314	0.223	0.156
Hydrogen production efficiency	0.040	0.032	0.063	0.016
Syngas production efficiency	0.468	0.402	0.243	0.160
Waste exergy ratio	0.532	0.597	0.756	0.839
Exergy recoverability ratio	0.351	0.351	0.505	0.542
Exergy destruction ratio	0.181	0.246	0.251	0.298
Environmental Impact Factor	1.556	1.900	3.385	5.372
Exergetic Sustainability Index	0.642	0.526	0.295	0.186

- In laboratory experiments, the gasification rates of coal may be slower than other fuels at the same temperature. This can cause coal build-up and eventually stop in the gasifier [132]. Therefore, gasification temperature should be regulated for preventing such unwanted conditions.
- The capacitance probe in the plasma gasifier is very sensitive to temperature and relative humidity. Any change in these two parameters can alter the accuracy of the previously calibrated measurement [144].
- Thermodynamic equilibrium cannot be achieved at low temperatures. This is a major challenge for modeling studies [160].
- In modeling studies, parameters such as tar modeling, duration of the reaction in the gasifier, and heat losses limit the applicability of the model to different plant designs [161].
- Pressure drops in gasifiers indicate another challenge that can result in poor syngas quality, and one of the challenges is that there is no standard in the literature for modeling tar formation, and since the catalyst effect is not taken into account in modeling studies, realistic results cannot be obtained when a catalyst is used [161].
- In some cases, the modeling of one-dimensional gasifiers contradicts actual practice as it is based on the assumption that any change in the reactor can occur only in the axial direction [161,162].
- Some ash components such as alkalis can be deposited deep within a refractory liner, and distance from feedstock to gasifier can reduce coal gasification efficiency [163].
- There may be rupture in pipes and melting in the valves due to high temperature on the gasifier and connection pipes and equipment, and the change in feed conditions and temperature/pressure makes it difficult to develop an efficient process model [164].
- It is necessary to clean the syngas produced because of the particles and impurities, and tar may occur as a result of gasification at low temperatures, and the system may need to be shut down after tar formation, after tar formation, the carrier line may be clogged. Also, increase in air pollution increases as a result of clogging of cleaning units with the formation of tar, producer gas has a highly explosive effect [165].
- The main disadvantage of the purification processes is that the tars are not cooled. It must first be removed directly from the hot gas, and system failure may occur as a result of tar accumulation [166].
- Workers in coal gasification can be exposed to many compounds, including asbestos, silica, lead, nickel, hydrocarbons, sulfur dioxide and sulfuric acid, and an excessive amount of lung cancer has been observed in workers associated with gasification of coal [167].
- Gasification of coal is one of the more water-intensive forms of energy generation. This can cause water pollution [168].
- The main investment cost is high, and high temperature reduces energy efficiency, and cost of small size gasifier at high pressure can be high, and use of CO_2 as a gasifying agent requires an external heat source [169].
- The abrasion and corrosion of the slag removal unit has a negative effect on the system [170].

Opportunities and strategic approaches

While there are numerous challenges with effective operation of gasification systems, there are many opportunities.

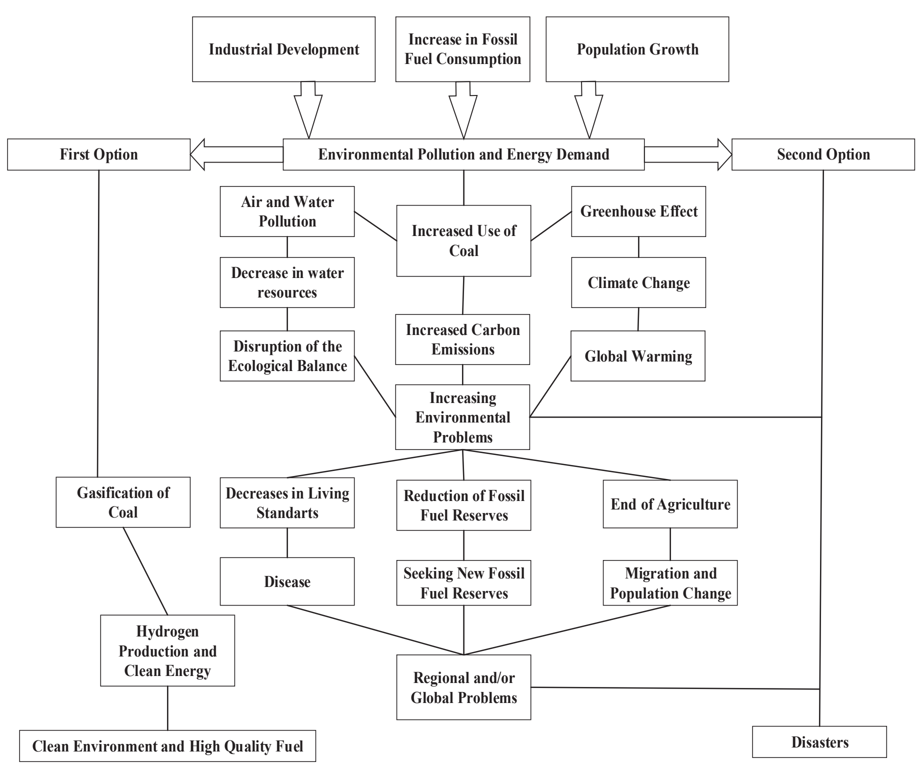

Fig. 5 – Scenarios resulting from the use of coal (Adapted from Ref. [179]).

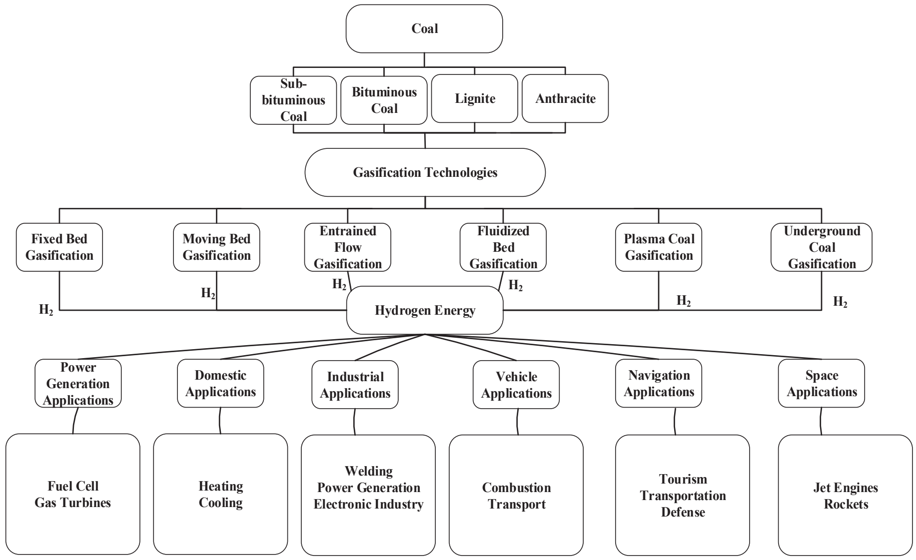

Fig. 6 – Some production and application options of hydrogen from coal gasification (Adapted from Ref. [176]).

The CO_2 released as a result of energy production by coal gasification is much lower compared to conventional methods [171,172]. Especially, of clean coal technologies, plasma gasification systems with high efficiency up to 57% may have a high contribution in reducing the emissions from coal through power generation [173]. From an environmental point of view, the damage to nature can be more reduced by applying plasma gasification for hydrogen production from coal. A large amount of ash and waste is released during the energy production carried out by conventional methods. When the same process is done with plasma coal gasification, very low slag output occurs. Thus, the disposal of hazardous wastes to be generated is realized. The calorific value of coal is very low compared to hydrogen. High purity hydrogen obtained by the separation of the syngas released by coal gasification by various methods can be used as clean fuel in different systems [174,175].

- Gasification of coal reduces the carbon footprint and greenhouse gas emissions compared to conventional methods [132].
- Coal gasification has more efficiency than traditional coal burning, and the fuels of diesel and gasoline are produced by liquefaction after coal gasification [168].
- Tar formation is prevented by plasma gasification method [165].

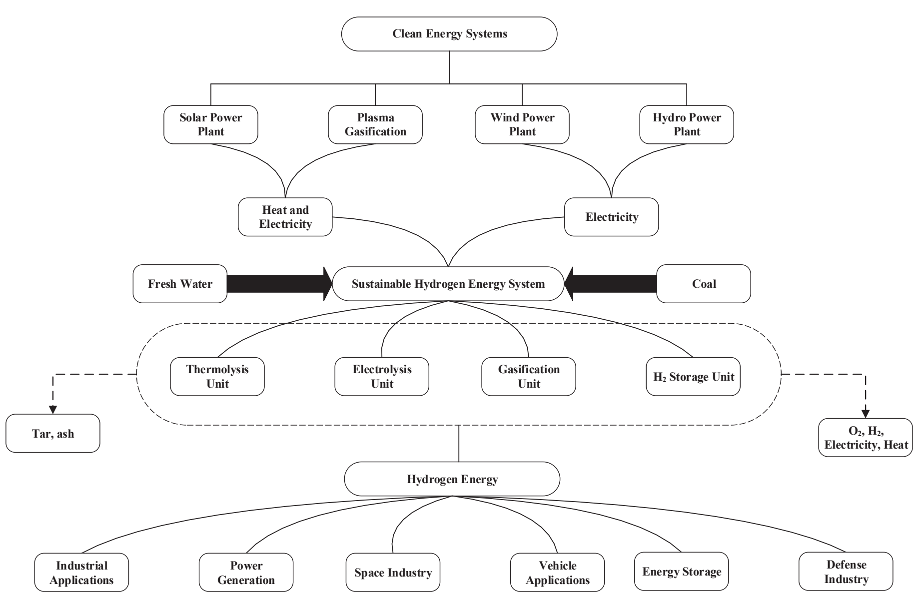

Fig. 7 – Environmentally friendly clean energy based hydrogen energy system (Adapted from Ref. [177]).

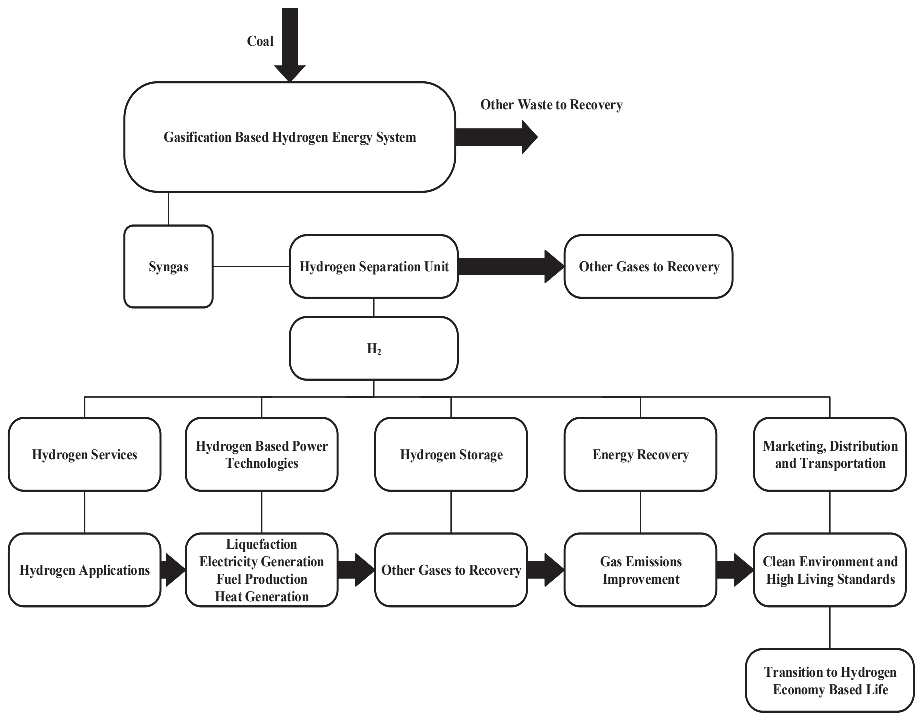

Fig. 8 – Coal gasification integrated hydrogen applications (Adapted from Ref. [177]).

- Use of steam increases the calorific value of the synthesis gas and provides low tar production [166].
- It is much cheaper to transport gas than to transport coal, and gasification units helps solve local pollution problems [168].
- Vitrified Material resulting from gasification can be used in road construction [159].

Coal is consumed in many industries including thermal power plants, iron and steel industry, transportation vehicles (ships, trains etc.) and many other sectors around the world. Increasing population, development of industry, increase in the use of coal and other fossil based fuels cause an increase in environmental pollution as well as energy demand. Two scenarios emerge as a result of the increase in environmental

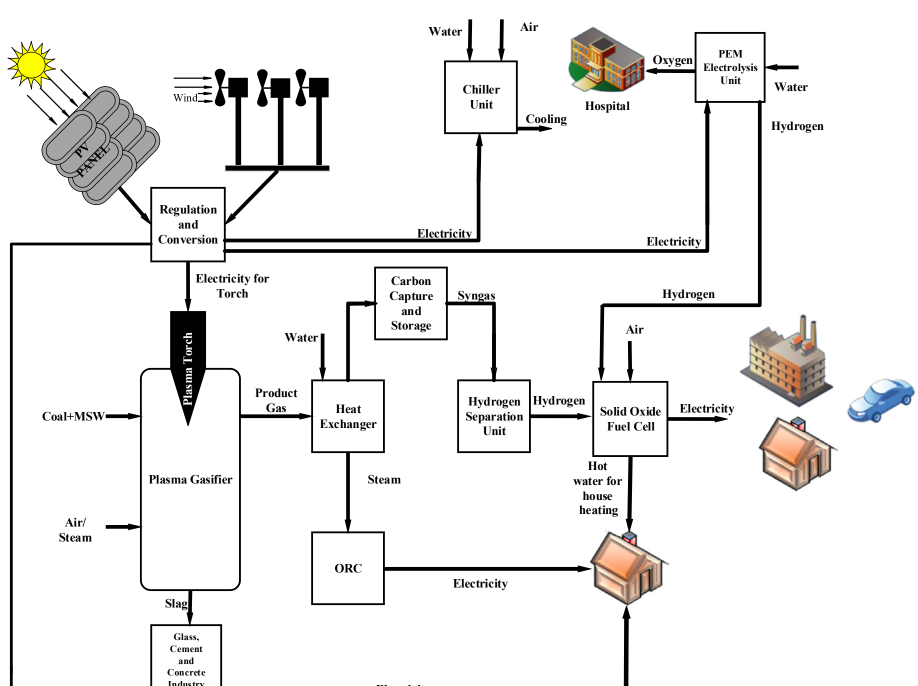

Fig. 9 – Renewable energy integrated plasma co-gasification based multi generation system.

pollution and energy demand. One includes the increase of environmental problems due to air and water pollution, greenhouse effect, deterioration of ecological balance, global warming Increase in environmental problems leads to regional and/or global problems. In the second scenario, as a result of the gasification of coal, hydrogen production and use of clean energy are encouraged to ensure a clean and sustainable environment, better living standards and high quality fuel. The environmental impacts of coal use and its alternative use are shown in the schematic illustration as in Fig. 5.

The relationship between gasification and production techniques and hydrogen use types is shown in Fig. 6. Based on the problems shown in Fig. 5, it is recommended to gasification of coal instead of fossil fuels to achieve a cleaner and more sustainable environment. Potential energy sources are divided into renewable and non-renewable energy sources. Coal constitutes an important part of non-renewable energy resources. Clean energy can be produced by using clean coal gasification technologies. Gasification of coal is done by fixed bed gasification, moving bed gasification, entrained flow gasification, fluidized bed gasification, plasma gasification and underground gasification techniques. Because of the harmful environmental effects of fossil fuel based power generation, renewable energy integrated power generation systems should be encouraged for clean energy or hydrogen production. In this regard, an environmentally friendly clean energy system is presented in Fig. 7. Hydrogen can be stored as clean fuel that can be used in many different applications from homes to the space industry. In this context, coal gasification integrated hydrogen applications are presented in Fig. 8.

Future directions

The power generation, storage and cooling systems can be designed to use the waste heat and hydrogen produced by applying plasma co-gasification process more efficiently. The future works related to plasma co-gasification can be experimental and numerical evaluation of the designed plasma co-gasification with carbon capture process system, power generation units, hydrogen production units, cooling unit in integrated plasma co-gasification system in Fig. 9.

A novel plasma co-gasification system for synthetic fuel from coal and organic wastes is illustrated in Fig. 9. In this system, the mixture of organic wastes and coal is converted into synthetic gas by applying steam/air plasma co-gasification process. The plasma torch is operated in co-gasification process, using the electricity generated in the photovoltaic panel and wind turbine. The raw synthesis gas released as a result of the co-gasification process passes through the heat exchanger. The refrigerant fluid (water) heated by exchanging heat from the synthesis gas in the heat exchanger turns into steam form. The released steam is released into the atmosphere as waste heat, but electricity is generated by replacing an organic Rankine cycle (ORC) using this waste heat. Synthesis gas from the heat exchanger is sent to the hydrogen separation unit. The hydrogen separated from the synthesis gas is sent to a SOFC unit for power generation. The electricity generated in the SOFC unit can be used in residential areas, transportation and industry. Hot water from SOFC unit can be used for heating applications. In addition, some of the electricity generated by photovoltaic panel and wind turbine system is used for cooling by chiller unit, and some for generating oxygen and hydrogen in the PEM electrolysis unit. Oxygen can be used for various applications in the hospitals. Schematic representation of the system is as follows.

Carbon capture and storage

Recently, carbon capture and storage process (CCS) has become an important research subject as a result of the CO_2 emissions. When the coal is burned or gasified in an energy system, the CO_2 is also produced as one of the harmful emissions, which is the main component of the greenhouse gases [178]. In order to reduce the effect of CO_2, the Carbon Capture and Storage Process that is divided into carbon capture with separation and carbon capture without separation [178,179] is applied and so considered to be the best way to capture CO_2 and store it in a safe medium during gasification process.

Concluding remarks

A comprehensive review is performed to discuss the hydrogen production options from coals and evaluate these comparatively for practical applications. The main findings of this comparative review are summarized below:

- Hydrogen concentration in the synthesis gas produced by utilizing plasma co-gasification is higher when steam is used as a gasifying agent.
- The amount of synthesis gas obtained from coal increases with the addition of municipal solid wastes.
- Plasma co-gasification process can more efficiently be used for converting coal and municipal solid wastes in to syngas.
- Reduced amounts of wastes (slag, ash, tar etc.) are released in the plasma gasification system when compared to other gasification methods.
- Plasma coal gasification appears to be more environmentally friendly, more efficient and sustainable than other conventional methods of generating energy from coal, in terms of the emissions.
- Plasma gasification system can be designed in smaller and modular sizes and capacities when compared to other gasification systems and conventional energy generation systems.
- The heat produced by the plasma gasification is high-temperature thermal energy and can be used for power generation and desalination purposes.
- Hydrogen produced by coal gasification can be utilized in many sectors, ranging from transportation to power generation and industrial to chemical.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

AC	Alternative Current
CH_4	Methane
C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6	Ethane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DC	Direct Current
DSS	Dried Sewage Sludge
Fe	Iron
Fig	Figure
h	Enthalpy
H_2	Hydrogen
HHV	Higher Heating Value
K	Potassium
LHV	Lower Heating Value
MCw	Microwave
N_2	Nitrogen
Na	Sodium
ORC	Organic Rankine Cycle
PSA	Pressure Swing Adsorption
Ref	Reference
RF	Radio Frequency
s	Entropy
SNG	Substitute Natural Gas
PKS	Palm Kernel Shells
LC	Indian Lignite Coal

Symbols

$\dot{E}_{in}$	Energy Inlet (kW)
$\dot{E}_{out}$	Energy Outlet (kW)
$\dot{Ex}_{dest}$	Exergy Destruction (kW)
$\dot{Ex}_{in}$	Exergy Inlet (kW)
$\dot{Ex}_{out}$	Exergy Outlet (kW)
$\dot{m}_{in}$	Mass Inlet (kg/h)
$\dot{m}_{out}$	Mass Outlet (kg/h)
$f_{envi}f_{envi}$	Environmental Impact Factor
r_{exd}	Exergy Destruction Ratio
r_{exr}	Exergy Recoverability Ratio
r_{wex}	Waste Exergy Ratio
η_{en}	Energy Efficiency
η_{ex}	Exergetic Efficiency
Θ_{esi}	Exergetic Sustainability Index

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