INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 10605–10614

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Hydrogen: A brief overview on its sources, production and environmental impact

Sema Z. Baykara *

Yildiz Technical University, Chemical Engineering Department, Topkapi, 34210, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 15 August 2017
Received in revised form
29 January 2018
Accepted 4 February 2018
Available online 5 March 2018

Keywords:
Hydrogen
Hydrogen sources
Hydrogen production
Climate change

ABSTRACT

A brief overview is presented involving the terms of availability of hydrogen, its properties and possible sources and its production methods, and finally, its relationship with renewable energy utilisation, environment and climate.

Solar hydrogen, preferably obtained from water, is confirmed once more to be the most environment and climate compatible (causing the least damage), energy source; though not necessarily the most economic one. Production cost of hydrogen obtained from terrestrial biomass, is not the lowest either, however carbon-neutral feature of terrestrial biomass renders it highly desirable in view of steep rise in global temperature.

Introduction

Growth in population and economy in the world are directly proportional to fossil fuel utilisation and environment deterioration [1–3]. The present situation in this relationship is shown in Table 1 [4–8]. Presently, 81% of total primary energy supply, and 66% of electricity generation are based on fossil fuels (coal, natural gas and oil), leading to almost 100% of CO_2 emissions in the world [9]. At current consumption rates, world's proven coal, oil and natural gas reserves are expected to last for approximately 200, 40 and 60 years. Peak production rates of liquid fuels, and natural gas seem likely to occur in 2005–2015 and in 2030 [10]. Afterwards, the overall resources will be in decline.

Sustainability of conventional fuels has been a major concern because of their depletable nature. Presently, the concern is rather focused on the rise in global temperature mainly due to GHG (greenhouse gas) emissions resulting from their processing and combustion [11].

Owing to efforts in the direction of transition to low carbon energy technology, experts hope to "bend down" the GHG emission curve by 2020 [12]. Cutting down the rate of global warming to 1.5 °C is another goal on which IPCC and COP are jointly working [13,14]. Using hydrogen as a fuel will definitely contribute to that effect.

A "sustainable energy source" would be one that is not substantially depleted by continued use, does not involve significant pollutant emissions or other environmental problems, health hazards or social injustices [15]. Renewable energy forms, especially hydrogen produced from water using solar energy comes very close to this definition.

Various studies are available involving all aspects of hydrogen technology and the rationale for the hydrogen energy system [16–21] including the present energy system, its depletable fossil fuels and their adverse effects on the

* *Corresponding author.*
E-mail address: szbaykara@gmail.com.
https://doi.org/10.1016/j.ijhydene.2018.02.022

Table 1 – Worldwide fossil fuel consumption and environmental damage 2015–2016 [4–8].

Fossil fuel used [4]	(in 10^{18} J per year)
Coal	112.5
Petroleum	208.6
Natural gas	126.6
Total	447.8
Damage on Environment [5,6]	(in 10^9 \$)
Coal	522.0
Petroleum	442.8
Natural gas	252.0
Total	1216.8
Effect on Economy and Society	
Population (total) [7]	7.4×10^9
Distribution of damage	\$ 164.4 per capita
Gross world product (WP) [8]	\$ $74,152.5 \times 10^9$
Distribution of WP	\$ 10,020.6 per capita
Total damage/WP	0.0164

Table 2 – Properties of hydrogen [16].

Molecular weight	2.016	Amu
ρ (gas)	0.0838	kg/m^3
HHV	141.90	MJ/kg
	11.89	MJ/m^3
LHV	119.90	MJ/kg
	10.05	MJ/m^3
T (boiling)	20.3	K
ρ (liquid)	70.8	kg/m^3
Critical point		
temperature	32.94	K
pressure	1284	kN/m^2
density	31.40	kg/m^3
T (self-ignition)	858	K
Ignition limits in air	4–75	(vol%)
Stoichiometric mixture in air	29.53	(vol%)
T (flame)	2318	K
D	0.61	cm^2/s
C_P	14.89	kJ (kg.K)

environment and climate change [22], the critical role of hydrogen as an energy currency [23], and issues related to climate change and hydrogen energy [1–3].

In the present study, a brief overview on hydrogen is presented including its sources, main production methods, and positive impact on the environment and global warming, with emphasis on rapidly informing the readers especially who are new to or outside of the field regarding the urgency of acceptance of hydrogen as an alternative. Possibility of wider information on the subjects covered is offered through cited references most of which are review papers.

Hydrogen

Hydrogen is not readily available on Earth in elemental form. However, it can be produced from its compounds found in natural or industrial sources. Hydrogen is the most abundant element in the universe, making up approximately 75% of all matter [24]. In Earth's crust, it is the tenth most abundant element, and it is found in combination with other elements. Hydrogen is not found in Earth's atmosphere since the Earth's gravitational pull is not strong enough (unlike Jupiter and Saturn) to retain the light weight H_2 molecules. Scientist believe that helium and hydrogen, were the first elements formed in the early stages of cosmic evolution.

Three isotopes of hydrogen are available: protium, deuterium and tritium. Consisting of one proton and one electron, protium is the main component of hydrogen, the simplest element. Although it is the lightest element, hydrogen has the highest energy content per unit mass among all fuels. Some of its properties are given in Table 2 [16].

Hydrogen is scarce on Earth's surface (0.14%), and it is found only in trace amounts (0.07%) in the atmosphere. Though quite uncommon, presence of hydrogen has been encountered in larger amounts in some wells containing nitrogen [25]. Small amounts of hydrogen may exist in mixtures with natural gas in crustal reservoirs.

Although a variety of technology at different scales have been developed for hydrogen as an energy carrier, it is widely used as chemical feedstocks in the industry.

Wide-scale use of hydrogen as a fuel would lead to escalation in production capacity by several folds. The energy input for hydrogen production is always greater than the energy output from hydrogen. Consequently, energy, as well as feed stocks, will be required to obtain hydrogen. Considering the levels of energy consumption in the world and the adverse effects of the present fossil based energy sources on the environment, renewable energy sources are ideal for sustainable hydrogen production [26,27].

Hydrogen production methods

Hydrogen gas has an important role in industrial processes, mostly as feedstocks. Presently, fossil fuels constitute the main sources for hydrogen production. Chemical grade hydrogen is possible by water electrolysis. Approximately 95% of the hydrogen produced is used captively [24]. As utilisation of hydrogen as a fuel grows and as global temperature keeps rising, it will be necessary to produce it at larger scale using diminishing amounts of fossil resources. Several detailed reviews on overall evaluation of hydrogen production methods are available [18,28–41].

Methods are available for hydrogen production from fossil fuels [16,42–63], especially from methane, the main constituent of natural gas [16,47–53,55–59] and coal [16,42,58,61–63], from biomass [16,60,63–80], water [16,81–137]; compounds like metal hydrides [16,138–142] and H_2S [143–152] and biological sources [16,153–165].

Various studies on hydrogen production costs are also available [11,21,28,34–37,40,41,71], allowing comparison of methods [18,28,107]. The results for solar hydrogen from water are presented in Table 3 [107] as an example.

Fossil based hydrogen production methods have commercialized mature technologies established at higher efficiency and lower product cost ranges. Natural gas is mostly methane, and the SMR (steam reforming of methane) process is widely used for hydrogen production from natural gas, at an efficiency range of 65–75%. Another process is partial oxidation of natural gas which has lower efficiency 50% [16]. For

Table 3 – Production cost of solar hydrogen relative to commercial hydrogen [107].

Solar process	Detail	$Cost/(cost)_j$	$Coast/(cost)_k$	$Cost/(cost)_l$
Water:				
a) Electrolysis	PVE (solar cell panels)	3.9	15.2	22.8
b) Electrolysis	STE (parabolic dish + steam turbine)	1.1	4.4	6.6
c) Electrolysis	STE (solar tower + steam turbine)	2.6	10.1	15.15
d) Thermolysis	SPH (parabolic dish)	3.3	12.5	18.75
e) Hybrid thermolysis	(b + d)	2.2	8.6	12.9
Coal:				
f) Solar gasification	SPH (solar tower) + KT type gasifier	0.8	2.9	4.35
g) Hybrid solar coal gasification	(f + commercial KT Process)	0.7	2.6	3.9
Thermochemical:				
h) Solar cycle	SPH (solar tower) + GA TC	1.9	7.3	10.95
i) Hybrid cycle	Mark 11 TC	1.6	6.2	9.3
Commercial Process:				
j) Electrolysis (water)	$ 0.10/kWh	1.0	3.8	5.0
k) Gasification (coal)	$ 10/ton coal, 15% FCR	0.3	1.0	1.5
l) SMR (Natural Gas)	[150]	0.2	0.67	1.0

GA: General Atomic.
KT: Koppers Totzek.
PVE: PV electricity.
SPH: Solar process heat.
STE: Solar thermal electricity.
TC: Thermochemical cycle.

coal gasification, Koppers-Totzek process is the leading technology, capable of producing up to 97% pure hydrogen. It may be possible to keep fossil-based hydrogen production in practice in the near term and mid term through application of carbon sequestration [54–58] and solar thermal processes [53,62,63,102,110].

Hydrogen can also be produced from **biomass** via pyrolysis/gasification [64–80] using a process similar to gasification of coal. However, since biomass has lower calorific value than coal larger size plants are required. Thermal methods are quite suitable for hydrogen production from bio-oil [77] and biogas [78], derivatives of biomass. Photochemical [79] and photoelectrochemical [80] processes based on photocatalytic degradation of organic matter, are being developed with the purpose of producing electricity and hydrogen from organic waste.

Various methods of hydrogen production from **water** are available including electrolysis [81–104], direct thermal decomposition or thermolysis [105–107], thermochemical processes [108–121] and photolysis [122–135].

The efficiency levels for water electrolysis may vary from 70 to 90% [81,92]. Various plants for PV electrolysis are operational world over [95–99]. Electrolysis by electricity from concentrated solar power (CSP) [100] or wind [103,104] is also possible. Based on life cycle analysis (LCA) studies [88], it has been shown that electrolysis processes powered by electricity from renewable energy sources have low global warming potential (GWP), less than 5 kg CO_2 eq/kgH_2, wind electrolysis having the lowest. Whereas for electrolysis using electricity from the grid, GWP can be as high as 30 kg CO_2 eq/kg H_2.

Thermochemical hydrogen production from water is possible through single step or multi step processes. Above 2000 K direct thermal decomposition of water is possible [105–107]. The extent of single-step water dissociation varies directly with temperature (from 1% at 2000 K to 34% at 3000 K). Lowering pressure has a favourable effect on the process. Hydrogen can be produced at relatively lower temperatures, through thermochemical cycles [16,108–121], where dissociation of water into hydrogen and oxygen is possible through two or more successive reaction steps involving redox materials such as sulfur and some metal oxides. Sulfur-based cycles can be operated at lower temperatures (T < 1200 K) relative to metal oxide cycles [114]. Nearly 2000–3000 thermochemical cycles have been studied, 20–30 of which may be suitable for large-scale hydrogen production. Efficiencies up to 40–50% can be reached with thermochemical cycles. Some examples are H_2SO_4–I_2, H_2SO_4–HBr, $CaBr_2$–Fe_2O_3 (UT-3) and $FeCl_2$ (Mark 9) cycles [83,108,119]. Thermochemical methods are suitable for high temperature solar energy utilization through CSP systems [105–107,110–114] and nuclear heat [110,119–121].

Hydrogen can be released from water via light-driven methods involving photobiological [123–126], photochemical [123,129–134] and photoelectrochemical systems [123,135–137]. These methods are at early stages of development and have considerably low efficiency levels presently. However anticipation for new break through via discovery of new catalytic materials continue.

Hydrogen production is possible through pyrolysis and hydrolysis of **metal hydrides**. Lithium and magnesium hydride (LiH, MgH_2), lithium and sodium borohydride ($LiBH_4$, $NaBH_4$), lithium and sodium aluminium hydride ($LiAlH_4$, $NaAlH_4$) are often considered [16,138–142].

Hydrogen sulfide is a potential source for hydrogen production and technology is being developed involving thermal, thermochemical, electrochemical, photochemical and plasmochemical methods that are at different levels of maturity [143–152].

Biohydrogen production with (micro)organisms [153–165] is a relatively new area involving direct and indirect biophotolysis of water; photo and dark fermentation, and microbial electrolysis of organic matter by bacteria. In biophotolysis, special microorganisms such as green algae and cynobacteria produce hydrogen by consuming and splitting water through their natural metabolic processes using sunlight [124–126,153–158]. Photodecomposition of organic compounds by photosynthetic bacteria [157–161] when exposed to near IR light, purple bacteria (non-sulfur) can produce hydrogen (with a special enzyme) by breaking down organic material. In dark fermentative hydrogen production from organic compounds [162–165] anaerobic bacteria can decompose organic material (without the aid of sunlight) into hydrogen and other products. In microbial electrolysis [155,156,165] a low voltage is produced at the anode of the cell as the bacteria decompose organic material. Hydrogen is produced at the cathode. Generally, additional energy is required. Hybrid biohydrogen systems are integrated systems where byproducts of one approach serve as inputs to another [124,154] and hydrogen is produced as a result.

Light-driven biohydrogen methods such as biophotolysis and photofermentation are mostly limited by low light conversion efficiencies. In dark fermentative processes, yields are limited by metabolic routes [155]. Microbial electrolysis cannot be self-sustaining since for improved yields, supply of excess voltage is required. Hybrid systems are considered for improving the performance of biohydrogen processes.

Evaluation and future possibilities for methods

Fossil based centralized hydrogen production methods have commercial, mature technology and established feedstock infrastructure. Although carbon sequestration helps extend utilization of fossil-based technology, large scale land damage caused due to extraction of fossil fuels and risk of oil spills in oceans during transportation of petroleum by tankers still remain to be dealt with.

Water electrolysis has well developed technology and uses electricity from the grid and the existing infrastructure. These present technologies are expected to supply the near-term hydrogen market as well.

Steam reforming of natural gas and coal gasification with carbon capture may continue during the midterm hydrogen market along with gasification of biomass and reforming of liquid fuels derived from biological sources, some of which already have infrastructure present.

The long term, hydrogen market may be supplied by water electrolysis using renewable electricity, thermochemical cycles; even by biological and photoelectrochemical methods; all with clean and sustainable technologies.

Economic aspects

Relatively new hydrogen production technologies, including the ones using renewable energy are not as costwise competitive presently, although they are highly pollution-free.

In the case of fossil-based (natural gas, oil and coal) hydrogen production, cost of manufacturing is lower than the “environmental cost” of using the fuel itself. Since that cost is negligible for hydrogen, it would be only logical to produce hydrogen from these fuels instead of directly using them.

Various studies evaluating hydrogen production methods in terms of efficiency, cost and environmental impact are available [18,21,28,88]. In view of these studies, hydrogen from water by thermochemical methods and by electrolysis using solar energy; hydrogen from biomass and fossil fuels using carbon sequestration may become mainstream hydrogen production technologies with large-scale plant capacities. However, small-scale distributed hydrogen production may also be possible via reforming of natural gas and water electrolysis using renewable electricity from the grid.

Hydrogen, environment and climate change

Main alternatives to the presently established fossil fuel energy system are the coal/synthetic fossil fuel system and the solar hydrogen system [16], although they are not equivalent in terms of environmental impact. Synthetic fossil fuels may offer convenient production routes, but they may involve equally or even more polluting processes compared to regular fossil fuels. On the other hand, solar hydrogen offers a clean ad permanent energy system since renewable solar energy and/or its derivatives (i.e. hydro, wind, wave) are used as primary energy inputs for production of hydrogen, a secondary energy source, also environmentally compatible [16].

In view of the three energy systems, environmental factors like pollution, vapor generation and environmental damage are at significantly low levels for the solar hydrogen energy system compared to the other energy systems (Table 4).

Table 4 – Environment related properties of the main energy systems [23].

Energy system	Pollutants (kg/GJ)						Vapor generation (10^{12} kg/y)			Environ-mental damage ratio[c]	Environ-mental compatibility factor
	CO_2	CO	SO_2	NO_x	HC	PM[a]	Energy system	Global warming	(%)[b]		
Fossil fuel	72.40	0.80	0.38	0.34	0.20	0.09	8.9	3900	0.782	18.24	0.055
Coal/Syntehic fosil fuel	100.00	0.65	0.50	0.32	0.12	0.14	9.3	3900	0.782	22.62	0.044
Solar-hydrogen energy	0.00	0.00	0.00	0.10	0.00	0.00	6.0	0.0	0.001	1.0	1.00

[a] Particulate matter.
[b] With respect to annual vapour generation due to solar heating (5×10^{17} kg/y).
[c] (Damage due to fuel)/(Damage due to solar hydrogen).

The disadvantages of the coal/synthetic fuel system and the advantages of the solar hydrogen system can be seen in Table 4 [16,23]. Emissions of CO_2, CO, SO_x, hydrocarbons and particulates are eliminated in the solar hydrogen system; NO_x will not form if flame combustion in air is avoided [16].

In Table 4 [16,23] In addition to depletion of natural resources, the adverse consequences of fossil and nuclear fuel utilisation at current rates include global warming, leading to climate change, acid rain, and risk of nuclear radiation. Following industrial revolution, greenhouse gases (mainly CO_2, CH_4, H_2O) emitted during combustion of fossil fuels have been contributing to the accelerating increase in the Earth's surface temperature. Whereas, originally, same gases (produced naturally in right proportion) have been instrumental in maintaining the global temperature around 15 °C [15] keeping incoming solar radiation at equilibrium with outgoing infrared energy.

Based on carbon dioxide data from 1958 (measured at Mauna Loa, Hawaii) and pre-1958 data (estimated from ice cores), scientists estimate that during the twentieth century these 'anthropogenic' emissions caused a rise in the earth's global mean surface temperature of 0.6 °C [166].

For half a million years before the twentieth-century, atmospheric concentrations of CO_2 have varied between about 200 and 300 parts per million by volume (ppmv). But during the twentieth century they rose beyond this range, increasing to 370 ppm by 2001. Projections by the Intergovernmental Panel on Climate Change (IPCC) suggest they could rise to around 700 ppmv by the end of the twenty-first century if no action is taken to limit emissions. The projection shown for 2100 is near the middle of the IPCC range [15]. If emissions are not reduced, the surface temperature is predicted to rise by 1.4–5.8 °C by the end of the twenty-first century, leading to frequent extremes in climate and about 0.5 m rise in sea levels resulting in inundation of low lands. Reduction in emissions in the range of 60–80% may be necessary for slowing down the process, which may be possible by switching to carbon-free energy.

Activities directed towards reversing the process of climate change have been accelerated since the eighties, and they are becoming more focused on commitment acts from states [167,168]. Perceived as a scientific and political issue, climate change has been under investigation by scientists for the past hundred years [167–177]. The possibility of changes in climate due to increase in accumulation rate of CO_2 in the atmosphere was first brought up by the Nobel laureate S. Arrhenius in 1879 [169].

In the 1st World Climate Conference which was held in 1979 under the auspices of World Meteorological Organisation (WMO), the subject of climate change was brought to public attention, and it was concluded that, long term dependence on fossil fuels and deforestation would result in CO_2 accumulation in the atmosphere which in turn would lead to variations in climate. Through a joint initiative of WMO and United Nations Environmental Program (UNEP), The Intergovernmental Panel on Climate Change (IPCC) was formed and held its 1st meeting in November 1988. First Evaluation Report of IPCC [170] was issued in August 1990. A supplement followed in 1992 [171].

One of the significant initiatives for keeping or reducing the greenhouse gas emissions at a certain level was the UN Framework Convention on Climate Change in June 1992, which was signed by 166 countries and the European Union (EU) within a year and which came into effect on March 21, 1994. Thus, the concept of sustainable growth started maturing.

The Kyoto Protocol involving an agreement for 5% reduction in GHG emissions was concluded in 1997. The protocol came into effect on February 16, 2005.

Various national initiatives against environmental damage and air pollution were also taken. The Clean Air Act in 1963 and the Clean Air Act Amendments (CAAA) in 1990 of the United States, the Canadian Environmental Protection Act (CEPA) in 1988 [173], and emission control regulations in European Union [174] in 1998 can be mentioned as fundamental examples. Regulations for emission control limit the extent to which plants and vehicles impact air quality. The emission characteristics can be influenced by the level of emission standards, required emission durability, fuel composition and in-use inspection and maintenance [175,176].

The Kyoto Protocol in 1997 [177] did not impose binding targets for the biggest polluters such as US, China and India.

The Paris accord in November 2015 invited more than 190 countries to cut down emissions within a United Nations sponsored plan *allowing 2°C increase in temperature* in terms of voluntary commitments for targets that involve measurement and report of progress, but that are not legally binding. For example, China's emissions may subside after 2030, and 28–30% decrease in GHGs may be considered in US by 2025. However, despite all pledges, 3.4 °C rise in global temperature seems inevitable in 21st century. The countries that are under risk of inundation by rising seas are naturally alarmed [178].

In COP23 held in Bonn (06–17 Nov. 2017) the tolerable increase in temperature has been targeted as 1.5 °C [14]

Hydrogen and terrestrial biomass

Terrestrial biomass is a renewable, widespread and abundant energy source which captures carbon dioxide (CO_2) that leads to the green-house effect in the atmosphere, through photosynthesis and keeps it within the carbon cycle [15,179]. Application of biochar, obtained from terrestrial biomass via pyrolysis, to soil [180] can provide a sink for CO_2 from the atmosphere. Solid biomass resources, a great majority of which are lignocellulosic, can be converted into gaseous fuels through thermochemical gasification involving successive drying, pyrolysis and gasification in the reactor stage. Mainly, hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), particulates, tar, ammonia (NH_3) and sulfur compounds are generally found in the resulting 'product gas'. Hydrogen is separated from synthesis gas (H_2 + CO) which is obtained from 'product gas' following cleaning, reforming and shift processes. Before separation of hydrogen, the mass lower heating value (LHV_{mass}) of the product gas may be around 4.65 MJ/kg [181,182], and the overall efficiency of the process is estimated as over 80% [181,183,184]. Electricity production with high efficiency (>70%) [185] is possible as well, via combining catalytic biomass gasification with solid oxide fuel cells (SOFC), in decoupled (external gasification) or direct (internal gasification) mode [186–189].

With this technology, 50% reduction in GHGs is anticipated using low cost/readily available feed stocks (biomass, tar, plastics, etc ...). Since less CO_2 production in pure form is expected, less carbon sequestration and less gas separation loads can be considered as additional gains [186].

Conclusion

Economic development, energy utilization, environment and climate are interrelated but "securing energy and environment at lowest cost" is becoming increasingly difficult. Although climate change has both natural and anthropogenic components, global warming due to greenhouse gases, especially CO_2, is the main contributor to anthropogenic climate change. According to current estimates, CO_2 content of the atmosphere will approach 400 ppm by 2010, and 600 ppm during the second half of the 21st century.

Even if all the pledges of the Paris agreement in November 2015 are met, the global temperature is expected to increase by 3.4 °C within the present century. Consequently, in COP23 (Bonn, 2017) a tolerable limit of 1.5°C rise has been agreed on.

The best alternative would be to sustain the economic growth level by switching to hydrogen economy and using renewable energy sources. Hydrogen produced from water and terrestrial biomass using solar energy will be the most sustainable energy currency in the long term. Timely implementation of educational, financial, legislative, social and technological initiatives are necessary to make this happen.

Acknowledgements

Projects 213M368 and 217M139 (TUBITAK) are acknowledged.

REFERENCES

[1] Baykara SZ. Ecohealth problems and climate change I: anthropogenic climate change and ecohealth: worldwide environmental damage. Book of Invited Background Papers. Istanbul: IFSSH World Congress Health Challenges of the Third Millenium; August 21–26, 2005. p. 295–313.
[2] Veziroglu TN. Ecohealth problems and climate change II: permanent solution to environmental problems: hydrogen energy system. Book of Invited Background Papers. Istanbul: IFSSH World Congress Health Challenges of the Third Millenium; August 21–26, 2005. p. 315–35.
[3] Veziroglu TN, Gurkan I, Padki MM. Remediation of greenhouse problem through replacement of fossil fuels by hydrogen. Int J Hydrogen Energy 1989;14(4):257–66.
[4] BP statistical review of world energy. 2016. bp.com.
[5] DOE/EIA-0484 International energy outlook, 2016. May 2016. www.eia.gov.
[6] Roston E. Climate change may be doubted by some but now it's the law, 11.08.2016. bloomberg.com.
[7] Population reference Bureau (www.prb.org).
[8] Gross domestic product, 2016. 1 February 2017. data.worldbank.org.
[9] International Energy Agency. Key world energy statistics. Technical Report. 2017. http://www.iea.org/publications/freepublications/publication/keyworld 2017_ FINAL_WEB.pdf. [Accessed 27 December 2017].
[10] BP Statistical Review of World Energy, (www.bp.corn).
[11] Kopp RE, Mignone BK. The US Government's social cost of carbon estimates after their first two years: pathways for improvement. Economics 2012;6. 2012-15, (https://doi.org/10.5018/economics-ejournal.ja.2012-15).
[12] Figueres C, Schellnhuber HJ, Whiteman G, Rockström J, Hobley A, Rahmstorf S. Three years to safeguard our climate. Nature 2017;546:593–5.
[13] Press Release IPCC special report on global warming of 1.5oC expert review of the first order draft and start of the third lead author meeting. 23 Oct. 2017. 2017/24/PR, http://www.ipcc.ch. retrieved on 25.12.2017.
[14] United Nations Conference of the Parties, Twenty-third session. 18 November 2017. Draft Decision 1/CP23, Retrieved December 03, 2017, from http://unfccc.int/resource/docs/2017/cop23/eng/l13.pdf.
[15] Boyle G, editor. Renewable energy, power for a sustainable future. Oxford: Oxford University Press; 2004.
[16] Veziroglu TN, Barbir F. Hydrogen energy technologies. Vienna: UNIDO; 1998.
[17] Veziroglu TN. Quarter century of hydrogen movement 1974–2000. Int J Hydrogen Energy 2000;25(12):1143–50.
[18] Dincer I, Zamfirescu C. Sustainable hydrogen production options and the role of IAHE. Int J Hydrogen Energy 2012;37:16266–86.
[19] Dutta S. A review of production, storage of hydrogen and is utilization as an energy resource. J Ind Eng Chem 2014;20:1148–56.
[20] Bockris JO'M. The origin of ideas on a Hydrogen Economy and its solution to the decay of the environment. Int J Hydrogen Energy 2002;27:731–40.
[21] Sinigaglia T, Lewiski F, Martins MES, Siluk JCM. Production, storage, fuel stations of hydrogen and its utilization in automotive applications-a review. Int J Hydrogen Energy 2017;42:24597–611.
[22] Barbir F, Veziroglu TN, Plass Jr HJ. Environmental damage due to fossil fuel use. Int J Hydrogen Energy 1990;15(10):739–50.
[23] Baykara SZ. Hydrogen as fuel: a critical technology? Int J Hydrogen Energy 2005;30(5):545–53.
[24] Chang R. Chemistry. Boston: McGraw Hill; 2002.
[25] Goebel E, Coveney Jr RM, Angino EE, Zeller EJ, Dreschoff GAM. Geology, Composition, isotopes of naturally occurring H_2/N_2 rich gas from wells near junction city, Kansas. Oil Gas J May 1994:217–22.
[26] Twidell J, Weir A. Renewable energy resources. London: E & FN Spon; 1986.
[27] Sorensen B. Renewable energy: a technical overview. Energy Pol 1991;19(4):386–91.
[28] Dincer I, Acar C. Review and evaluation of hydrogen production methods for better sustainability. Int J Hydrogen Energy 2015;40:11094–111.
[29] Acar C, Dincer I. Comparative assessment of hydrogen production methods from renewable and non-renewable sources. Int J Hydrogen Energy 2014;39:1–12.
[30] Chaubey R, Sahu S, James OO, Maity S. A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources. Renew Sustain Energy Rev 2013;23:443–62.
[31] Dincer I. Green methods for hydrogen production. Int J Hydrogen Energy 2012;37:1954–71.
[32] Holladay JD, Hu J, King DL, Wang Y. An overview of hydrogen production technologies. Catal Today 2009;139:244–60.
[33] Freedom CAR& Fuel Partnership, Hydrogen production overview of technology options, Website: http://www.

energetics.com/resourcecenter/products/communication/documents/hydrogen-productionbrochure.pdf [Accessed on 19 December 2017].
[34] Mueller-Langer F, Tzimas E, Kaltchmitt M, Peteves S. Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term. Int J Hydrogen Energy 2007;32:3797–810.
[35] Ngoh SK, Njomo D. An overview of hydrogen gas production from solar energy. Renew Sustain Energy Rev 2012;16:6782–92.
[36] Trainham JA, Newman J, Bonino CA, Hoertz PG, Akunuri N. Whither solar fuels? Curr Options Chem Eng 2012;1:204–10.
[37] Yadav D, Banerjee R. A review of solar thermochemical processes. Renew Sustain Energy Rev 2016;54:497–532.
[38] Koroneos C, Rovas D. A review on exergy comparison of hydrogen production method from renewable energy sources. Energy Environ Sci 2012;5:6640–51.
[39] Yılmaz F, Balta MT, Selbaş R. A review of solar based hydrogen production methods. Renew Sustain Energy Rev 2016;56:171–8.
[40] Abanades A. The challenge of hydrogen production for the transition to a CO_2-free economy. Agron Res Biosyst Eng Spec Issue 2012;1:11–6.
[41] Bartels JR, Pate MB, Olson NK. An economic survey of hydrogen production from conventional and alternative energy sources. Int J Hydrogen Energy 2010;35:8371–84.
[42] Steinberg M, Cheng HC. Modern and prospective technologies for hydrogen production from fossil fuels. In: Veziroglu TN, Protsenko AN, editors. Hydrogen energy progress, VII. Oxford: Pergamon Press; 1988. p. 699–740.
[43] Muradov NZ, Veziroglu TN. From hydrocarbon to hydrogen-carbon to hydrogen economy. Int J Hydrogen Energy 2005;30:225–37.
[44] Mitchell WL. Development of a partial oxidation reformer for liquid fuels. In: Proc. Fuel cells for transportation TOPTEC: addressing the fuel infrastructure issue. Alexandria, VA: SAE, Warrendale, PA; 1996.
[45] Bae J, Lee S, Kim S, Oh J, Choi S, Bae M, et al. Liquid fuel processing for hydrogen production: a review. Int J Hydrogen Energy 2016;41:19990–20022.
[46] Nahar G, Dupont V. Hyrogen production from simple alkanes and oxygenated hydrocarbons over ceria-zirconia supported catalysts: Review. Renew Sustain Energy Rev 2014;32:777–96.
[47] Figen HE, Baykara SZ. Effect of ruthenium addition on molybdenum catalysts for syngas production via catalytic partial oxidation of methane in a monolithic reactor. Int J Hydrogen Energy 2018;32(2):1129–38.
[48] Abbas HF, Wan Daud WMA. Hydrogen production of methane decomposition: a review. Int J Hydrogen Energy 2010;35:1160–90.
[49] Amin AM, Croiset E, Epling W. Review of methane catalytic cracking for hydrogen production. Int J Hydrogen Energy 2011;36:2904–35.
[50] Enger BC, Lodeng R, Holmen A. A review of catalytic partial oxidation of methane to synthesis gas with emphasis on reaction mechanism over transition metal catalysts. Appl Catal Gen 2008;346:1–27.
[51] Figen HE, Baykara SZ. Hydrogen production by partial oxidation of methane over Co based Ni and Ru monolithic catalysts. Int J Hydrogen Energy 2015;40(24):7439–51.
[52] Barelli L, Bidini G, Gallorini F, Servili S. Hydrogen production through sorption-enhanced steam methane reforming and membrane technology: a review. Energy 2008;33:554–70.
[53] Agrafiotis C, Von Storch H, Roeb M, Sattler C. Solar thermal reforming of methane feedstocks for hydrogen and syngas production-a review. Renew Sustain Energy Rev 2014;29:656–82.
[54] Lynum S. CO_2-Free hydrogen from hydrocarbons-the Kvaerner CB&H process. In: 10th world hydrogen energy conference, Cocoa Beach, FL; June 1994.
[55] Yan W, Hoekman K. Production of CO_2-free hydrogen from methane dissociation: a review. Environ Prog Sustain Energy 2014;33(1):213–9.
[56] Ashik UPM, Wan Daud WMA, Abbas HF. Production of greenhouse gas free hydrogen by thermocatalytic decomposition of methane –a review. Renew Sustain Energy Rev 2015;44:221–56.
[57] Gaudernack B, Lynum S. Hydrogen from natural gas without release of CO_2 to the atmosphere. Int J Hydrogen Energy 1998;23(12):1087–93.
[58] Damen K, Van Troost M, Faaij A, Turkenburg W. A comparison of electricity and hydrogen production systems with CO_2 capture and storage, Part A: review and selection of promising conversion and capture technologies. Prog Energy Combust Sci 2006;32:215–46.
[59] Dufour J, Serrano DP, Galvez JL, Morena J, Garcia C. Life cycle assessment of processes for hydrogen production. Environmental feasibility and reduction of greenhouse gases emissions. Int J Hydrogen Energy 2009;34:1370–6.
[60] Mujeebu MA. Hydrogen and syngas production by superadiabatic combustion-A review. Appl Energy 2016;173:210–24.
[61] Rand DAJ, Dell RM. Fuels-hydrogen production: coal gasification. Encycl Elecrochem Power Sources 2009:276–92.
[62] Baykara SZ, Bilgen E. Synhesis gas and H_2 production from solar gasification of Albertan coal. Energy Convers Manag 1985;25(4):391–8.
[63] Zeng K, Gauthier D, Soria J, Mazza G, Flamant G. Solar pyrolysis of carbonaceous feedstocks: a review. Sol Energy 2017;156:73–92.
[64] National Hydrogen Association. The hydrogen technology assessment, Phase I, A Report for the NASA. Washington, D.C. 1991.
[65] Kalinci Y, Hepbasli A, Dincer I. Biomass-based hydrogen production: a review and analysis. Int J Hydrogen Energy 2009;34:8799–817.
[66] Abuadala A, Dincer I. A review on biomass-based hydrogen production and potential applications. Int J Energy Res 2012;36:415–55.
[67] Chen D, He L. Towards an efficient hydrogen production from biomass: a review of processes and materials. ChemCatChem 2011;3:490–511.
[68] Levin DB, Chahine R. Challenges for renewable hydrogen production from biomass. Int J Hydrogen Energy 2010;35:4962–9.
[69] Hosseini SE, Wahid MA, Jamil MM, Azli AAM, Misbah MF. A review on biomass-based hydrogen production for renewable energy supply. Int J Energy Res 2015;39:1597–615.
[70] Tanksale A, Beltramini JN, Lu GM. A review of catalytic hydrogen production processes from biomass. Renew Sustain Energy Rev 2010;14:166–82.
[71] Uddin MN, Wan Daud WMA, Abbas HF. Potential hydrogen and non-condensable gases production from biomass pyrolysis: insights into the process variables. Renew Sustain Energy Rev 2013;27:204–24.
[72] Parthasarathy P, Narayanan KS. Hydrogen production from steam gasification of biomass: influence of process parameters on hydrogen yield – a review. Renew Energy 2014;66:570–9.
[73] Hossain MA, Jewaratnam J, Ganesan P. Prospect of hydrogen production from oil palm biomass by thermochemical process – a review. Int J Hydrogen Energy 2016;41:16637–55.
[74] Udomsirichakorn J, Salam PA. Review of hydrogen-enriched gas production from steam gasification of biomass: the

prospect of CaO-based chemical looping gasification. Renew Sustain Energy Rev 2014;30:565–79.
[75] He C, Chen CL, Giannis A, Yang Y, Wang JY. Hydrothermal gasification of sewage sludge and model compounds for renewable hydrogen production: a review. Renew Sustain Energy Rev 2014;39:1127–42.
[76] Vaidya PD, Lopez-Saanchez JA. Review of hydrogen production by catalytic aqueous-phase reforming. Chem Select 2017;2:6563–76.
[77] Chattanathan SA, Adhikari S, Abdoulmoumine N. A review on current status of hydrogen production from bio-oil. Renew Sustain Energy Rev 2012;16:2366–72.
[78] Nahar G, Mote D, Dupont V. Hydrogen production from reforming of biogas: review of technological advances and an Indian perspective. Renew Sustain Energy Rev 2017;76:1032–52.
[79] Lianos P. Production of electricity and hydrogen by photocatalytic degradation of organic wastes in a photoelectrochemical cell. The concept of the photofuelcell: a review of a re-emerging research field. J Hazard Mater 2011;185:575–90.
[80] İbrahim N, Kamarudin SK, Minggu LJ. Biofuel from biomass via photo-electrochemical reactions: an overview. J Power Sources 2014;259:33–42.
[81] Bonner M, Botts T, McBreen J, Mezzina A, Salzano F, Yang C. Status of advanced electrolytic hydrogen production in the United States and abroad. Int J Hydrogen Energy 1984;9(4):269–75.
[82] Dutta S. Technology assessment of advanced electrolytic hydrogen production. Int J Hydrogen Energy 1990;15(6):379–86.
[83] Wendt H. Water splitting methods. In: Winter CJ, Nitsch J, editors. Hydrogen as an energy carrier. Springer-Verlag, Berlin Heidelberg; 1988. p. 166–238.
[84] Liepa MA, Borhan A. High-temperature steam electrolysis: technical and economic evaluation of alternative process designs. Int J Hydrogen Energy 1986;11(7):435–42.
[85] Rashid MM, Al Mesfer MK, Naseem H, Danish M. Hydrogen production by water electrolysis: a review of alkaline water electrolysis, PEM water electrolysis and high temperature water electrolysis. Int J Eng Adv Technol 2015;4(3):80–93.
[86] Zeng K, Zhang D. Recent progress in alkaline water electrolysis for hydrogen production and applications. Prog Energy Combust Sci 2010;36:307–26.
[87] El-Bassuoni AMA, Sheffield JW, Veziroglu TN. Hydrogen and fresh water production from sea water. Int J Hydrogen Energy 1982;7(12):919–23.
[88] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis: a review. J Clean Prod 2014;85:151–63.
[89] Monk N, Watson S. Review of pulsed power for efficient hydrogen production. Int J Hydrogen Energy 2016;41:7782–91.
[90] Wang M, Wang Z, Gong X, Guo Z. The intensification technologies to water electrolysis for hydrogen production-A review. Renew Sustain Energy Rev 2014;29:573–88.
[91] Hancock Jr OG. A photovoltaic-powered water electrolyzer: its performance and economics. In: Veziroglu TN, Taylor JB, editors. Hydrogen energy progress V. New York: Pergamon Press; 1984. p. 335–44.
[92] Carpetis C. An assessment of electrolytic hydrogen production by mans of photovoltaic energy conversion. Int J Hydrogen Energy 1984;9(12):969–92.
[93] Siegel A, Schott T. Optimization of photovoltaic hydrogen production. Int J Hydrogen Energy 1988;13(11):659–78.
[94] Steeb H, Brinner A, Bubmann H, Seeger W. Operation experience of a 10 kW PV-electrolysis system in different power matching modes. In: Veziroglu TN, Takahashi PK, editors. Hydrogen energy progress VIII, vol. 2. New York: Pergamon Press; 1990. p. 691–700.
[95] Blank H, Szyszka A. Solar hydrogen demonstration plant in neunburg vorm Wald. In: Veziroglu TN, Derive C, Pettier J, editors. Hydrogen energy progress IX, vol. 2. Paris: M.C.I.; 1992. p. 677–86.
[96] Grasse W, Oster F, Aba-Oud H. HYSOLAR: the German-Saudi arabian Program on solar Hydrogen-5 Years of experience. Int J Hydrogen Energy 1992;17(1):1–8.
[97] Lehman P, Chamberlain CE. Design of a photovoltaic-hydrogen-fuel cell energy system. Int J Hydrogen Energy 1991;16(5):349–52.
[98] Lund PD. Optimization of stand alone photovoltaic system with hydrogen storage for total energy self-sufficiency. Int J Hydrogen Energy 1991;16(11):735–40.
[99] Gaicia-Conde AG, Rosa F. Solar hydrogen production: a Spanish experience. In: Veziroglu TN, Derive C, Pettier J, editors. Hydrogen energy progress IX, vol. 2. Paris: M.C.I.; 1992. p. 723–32.
[100] Gahleitner G. Hydrogen from renewable electricity: an international review of power-to-gas pilot plants for stationary applications. Int J Hydrogen Energy 2013;38:2039–61.
[101] Kim J, Riviera JL, Meng TY, Laratte B, Chen S. Review of life cycle assessment of nanomaterials in photovoltaics. Sol Energy 2016;133:249–58.
[102] Coelho B, Oliveira AC, Mendes A. Concentrated solar power for renewable electricity and hydrogen production from water-a review. Energy Environ Sci 2010;3:1398–405.
[103] Sherif SA, Barbir F, Veziroglu TN. Wind energy and the hydrogen economy – review of the technology. Sol Energy 2005;78:647–60.
[104] Genc MS, Çelik M, Karasu İ. A review on wind energy and wind-hydrogen production in Turkey: a case study of hydrogen production via electrolysis system supplied by wind energy conversion system in Central Anatolian Turkey. Renew Sustain Energy Rev 2012;16:6631–46.
[105] Baykara SZ, Bilgen E. An overall assessment of hydrogen production by solar water thermolysis. Int J Hydrogen Energy 1989;14(12):881–9.
[106] Baykara SZ. Experimental solar water thermolysis. Int J Hydrogen Energy 2004;29(14):1459–69.
[107] Baykara SZ. Hydrogen production by direct solar thermal decomposition of water, possibilities for improvement of process efficiency. Int J Hydrogen Energy 2004;29(14):1451–8.
[108] Engels H, Funk JE, Hesselmann K, Knoche KF. Thermochemical hydrogen production. Int J Hydrogen Energy 1987;12(5):291–5.
[109] Funk JE. Thermochemical hydrogen production: past and present. Int J Hydrogen Energy 2001;26:185–90.
[110] Steinfeld A. Solar thermochemical production of hydrogen-a review. Sol Energy 2005;78:603–15.
[111] Abanades S, Charvin P, Flamant G, Neveu P. Screening of water-splitting thermochemical cycles potentially attractive for hydrogen production by concentrated solar energy. Energy 2006;31:2805–22.
[112] D'Souza L. Thermochemical hydrogen production from water using reducible oxide materials: a critical review. Mater Renew Sustain Energy 2013;2(7):1–12.
[113] Xing H, Yuan Y, Huiyuan Z, Yong S, Bingxi L, Heping T. Solar thermochemical hydrogen production using metallic oxides. Energy Sources Part A Recovery Util Environ Eff 2017;39(3):257–63.

[114] Sattler C, Roeb M, Agrafiotis C, Thomey D. Solar hydrogen production via sulphur based thermochemical water-splitting. Sol Energy 2017;156:30–47.
[115] Balta MT, Dincer I, Hepbasli A. Geothermal-based hydrogen production using thermochemical and hybrid cycles: a review and analysis. Int J Energy Res 2010;34:757–75.
[116] Wang ZL, Naterer GF, Gabriel KS, Gravelsins R, Daggupati VN. Comparison of sulfur-iodine and copper-chlorine thermochemical hydrogen production cycles. Int J Hydrogen Energy 2010;35:4820–30.
[117] Rosen MA. Advances in hydrogen production by thermochemical water decomposition: a review,. Energy 2010;35:1068–76.
[118] Agrafiotis C, Roeb M, Sattler C. A review on solar thermal syngas production via redox pair-based water/carbon dioxide splitting thermochemical cycles. Renew Sustain Energy Rev 2015;42:254–85.
[119] Yalcin SA. Review of nuclear hydrogen production. Int J Hydrogen Energy 1989;4(5):551–61.
[120] Dincer I, Balta MT. Potential thermochemical and hybrid cycles for nuclear-based hydrogen production. Int J Energy Res 2011;35:123–37.
[121] Bicer Y, Dincer I. Life cycle assessment of nuclear-based hydrogen and ammonia production options: a comparative evaluation. Int J Hydrogen Energy 2017;42:21559–70.
[122] Bull SR. Hydrogen production by photoprocesses. In: Proc. Int. renewable energy conf., Honolulu, Hawaii; 1988. p. 413–26.
[123] Willner I, Steinberger-Willner B. Solar hydrogen production through photo-biological, photochemical and photoelectrochemical assemblies. Int J Hydrogen Energy 1988;13(10):593–604.
[124] Das D, Veziroğlu TN. Advances in biological hydrogen production processes. Int J Hydrogen Energy 2008;33:6046–57.
[125] Martin BA, Frymier PD. A review of hydrogen production by photosynthetic organisms using whole-cell and cell-free systems. Appl Biochem Biotechnol 2017;183:503–19.
[126] Khetkorn W, Rastogi RP, Incharoensakdi A, Lindblad P, Madamwar D, Pandey A, et al. Microalgal hydrogen production: a review. Bioresour Technol 2017;243:1194–206.
[127] Arifin K, Majlan EH, Wan Daud WR, Kassim MB. Bimetallic complexes in artificial photosynthesis for hydrogen production: a review. Int J Hydrogen Energy 2012;37:3066–87.
[128] Sharma P, Kolhe ML. Review of sustainable solar hydrogen production using photon fuel on artificial leaf. Int J Hydrogen Energy 2017;48:22704–12.
[129] İsmail AA, Bahnemann DW. Photochemical splitting of water for hydrogen production by photocatalysis: a review. Sol Energy Mater Sol Cells 2014;128:85–101.
[130] Acar C, Dincer I, Naterer GF. Review of photocatalytic water-splitting methods for sustainable hydrogen production. Int J Energy Res 2016;40:1449–73.
[131] Ahmad H, Kamarudin SK, Minggu LJ, Kassim M. Hydrogen from photo-catalytic water splitting process: a review. Renew Sustain Energy Rev 2015;43:599–610.
[132] Acar C, Dincer I, Zamfirescu C. A review of selected heterogeneous photocatalysts for hydrogen production. Int J Energy Res 2014;38:1903–20.
[133] Ni M, Leung MKH, Leung DYC, Sumathy K. A review and recent developments in photocatalytic water-splitting using TiO_2 for hydrogen production. Renew Sustain Energy Rev 2007;11:401–25.
[134] Sahoo DP, Rath D, Nanda B, Parida KM. Transition metal/metal oxide modified MCM-41 for pollutant degradation and hydrogen energy production: a review,. RSC Adv 2015;5:83707–24.
[135] Getoff N. Photoelectrochemical and photocatalytic methods of hydrogen production: a short review. Int J Hydrogen Energy 1990;15(6):407–17.
[136] Wang M, Chen L, Sun L. Recent progress in electrochemical hydrogen production with earth-abundant metal complexes as catalyst. Energy Environ Sci 2012;5:6763–78.
[137] Acar C, Dincer I. A review and evaluation of photoelectrode coating materials and methods for photoelectrochemical hydrogen production. Int J Hydrogen Energy 2016;41:7950–9.
[138] Fakioglu E, Yürüm V, Veziroglu TN. A review of hydrogen storage systems based on boron and its compounds. Int J Hydrogen Energy 2004;29(2):1371–6.
[139] Patel N, Miotello A. Progress in Co-B related catalyst for hydrogen production by hydrolysis of boron hydrides: a review and the perspectives to substitute noble metals. Int J of Hydrogen Energy 2015;40:1429–64.
[140] Moussa G, Moury R, Demirci UB, Sener T, Miele P. Boron-based hydrides for chemical hydrogen storage. Int J Energy Res 2013;37:825–42.
[141] Demirci UB. The hydrogen cycle with the hydrolysis of sodium borohydride: a statistical approach for highlighting the scientific/technical issues to prioritize in the field. Int J Hydrogen Energy 2015;40:2673–91.
[142] Liu BH, Li ZP. A review: hydrogen generation from borohydride hydrolysis reaction. J Power Sources 2009;187:527–34.
[143] Guldal NO, Figen HE, Baykara SZ. Perovskite catalysts for hydrogen production from hydrogen sulfide. Int J Hydrogen Energy 2018;43(2):1038–46.
[144] Zaman J, Chakma A. Production of hydrogen and sulphur from hydrogen sulphide. Fuel Process Technol 1995;44:159–98.
[145] Reverberi AP, Klemes JJ, Varbanov PS, Fabiano B. A review on hydrogen production from hydrogen sulphide by chemical and photochemical methods. J Clean Prod 2016;136:72–80.
[146] Guldal NO, Figen HE, Baykara SZ. New catalysts for hydrogen production from H2S: preliminary results. Int J Hydrogen Energy 2015;40(24):7452–8.
[147] Guldal NO, Figen HE, Baykara SZ. Production of hydrogen from hydrogen sulfide with perovskite type catalysts: $LaMO_3$. Chem Eng J 2017;313:1354–63.
[148] Cox BG, Clarke PF, Pruden BE. Economics of thermal dissociation of H2S to produce hydrogen. Int J Hydrogen Energy 1998;23(7):531–44.
[149] Midilli A, Ay M, Kale A, Veziroglu TN. A parametric investigation of hydrogen energy potential based on H_2S in Black Sea deepwaters. Int J Hydrogen Energy 2007;32:117–24.
[150] Baykara SZ, Figen EH, Kale A, Veziroglu TN. Hydrogen from H_2S in the black sea. Int J Hydrogen Energy 2007;32(9):1246–50.
[151] Petrov K, Baykara SZ, Ebrasu D, Gulin M, Veziroglu A. An assessment of electrolytic hydrogen production from H_2S in Black Sea waters. Int J Hydrogen Energy 2011;36(15):8936–42.
[152] Ipsakis D, Kraia TZ, Marnellos G, Ouzounidou M, Voutetakis SS, Dittmeyer R, et al. An electrocatalytic membrane-assisted process for hydrogen production from H_2S in Black Sea: preliminary results. Int J Hydrogen Energy 2015;40(24):7530–8.
[153] Levin DB, Pitt L, Love M. Biohydrogen production and limitations to practical application. Int J Hydrogen Energy 2004;29(2):173–85.
[154] Das D, Veziroglu TN. Hydrogen production by biological processes: a survey of literature. Int J of Hydrogen Energy 2001;26:13–28.

[155] Hallenbeck PC, Abo-Hashesh M, Ghosh D. Strategies for improving biological hydrogen production. Bioresour Technol 2012;110:1–9.
[156] Lee HS, Vermaas WFJ, Rittmann BE. Biological hydrogen production: prospects and challenges. Trend Biotechnol 2010;28(5):262–71.
[157] Eroglu E, Melis A. Photobiological hydrogen production: recent advances and state of the art. Bioresour Technol 2011;102:8403–13.
[158] Singh L, Wahid ZA. Methods for enhancing bio-hydrogen production from biological process: a review. J Ind Eng Chem 2015;21:70–80.
[159] Elsharnouby O, Hafez H, Nakhla G, El Naggar MH. A critical literature review on biohydrogen production by pure cultures. Int J Hydrogen Energy 2013;38:4945–66.
[160] Zhang Q, Wang Y, Zhang Z, Lee DJ, Zhou X, Jing Y, et al. Photo-fermentative hydrogen production from crop residue: a mini review,. Bioresour Technol 2017;229:222–30.
[161] Zhang Z, Zhou X, Hu J, Zhang T, Zhu S, Zhang Q. Photo-bioreactor structure and light-heat-mass transfer properties in photo-fermentative bio-hydrogen production system: a mini review. Int J Hydrogen Energy 2017;48:12143–52.
[162] Sivagurunathan P, Kumar G, Bakonyi P, Kim SH, Kobayashi T, Xu KQ, et al. A critical review on issues and overcoming strategies for the enhancement of dark fermentative hydrogen production in continuous systems. Int J Hydrogen Energy 2016;41:3820–36.
[163] Sivagurunathan P, Kumar G, Kim SH, Kobayashi T, Xu KQ, Guo W, et al. Enhancement strategies for hydrogen production from wastewater: a review. Curr Org Chem 2016;20:2744–52.
[164] Bakonyi P, Nemestothy N, Simon V, Belafi-Bako K. Fermentative hydrogen production in anaerobic membrane bioreactors: a review,. Bioresour Technol 2014;156:357–63.
[165] Kadier A, Simayi Y, Abdeshahian P, Azman NF, Chandrasekhar K, Kalil MS. A comprehensive review of microbial electrolysis cells (MEC) reactor designs and configurations for sustainable hydrogen gas production. Alexandria Eng J 2016;55:427–43.
[166] Intergovernmental Panel on Climate Change. Climate change 200: the scientific basis. Cambridge University Press; 2001.
[167] Organisation for economic co-operation and development. Action against climate change. The Kyoto protocol and beyond. Paris: OECD; 1999.
[168] Organisation de cooperation et de developpement economiques. Changement clirnatique: les politiques nationales et le Protocole de Kyoto. Paris: OECD; 1999.
[169] Türkeş M. From Toronto 1988 to Berlin 1995 climate change accord. Sci Technol June 1995:46–9 (in Turkish).
[170] Houghton JT, Jenkins GJ, Ephraums JJ, editors. Climate change: the IPCC scientific assessment. Cambridge: Cambridge University Press; 1990.
[171] Houghton JT, Callander BA, Varney SK. Climate change 1992, the supplementary report to the IPCC scientific assessment. Cambridge: Cambridge University Press; 1992.
[172] Brown P, Wilson J. US in plan to bypass kyoto protocol. Guardian; 28 July 2005.
[173] Montgomery CW. Environmental geology. Boston: McGraw-Hill; 2003.
[174] Directive on emissions from passenger cars and light-duty commercial vehicles. European automobile manufacturers.
[175] European Commission press release (IP/98/734): Commissionand ACEA agrees on CO_2 emission from cars, 29 July 1998, Brussels. http://europa.eu/rapid/press-release_IP-98-734_en.htm?locale=en
[176] Lenz HP, Cozzarini C. Emissions and air quality. Warrendale PA: Society of Automotive Engineers Inc; 1999.
[177] Parry M, Arnell N, Hulme M, Nicholls R, Livermore M. Adapting to the inevitable. Nature 1988;395:741.
[178] Roston E. Climate change may be doubted by some but now it's the law. 11.08.2016. bloomberg.com.
[179] Ko C, Chaiprapat S, Kim L, Hadi P, Hsu S. Carbon sequestration potential via energy harvesting from agricultural biomass residues in Mekong River basis, Southeast Asia. Renew Sustain Energy Rev 2016;68:1051–62.
[180] Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems-a review. Mitig Adapt Strategies Glob Change 2006;11:403–27.
[181] Ersöz A, DurakÇetin Y, Sarıoğlan A, Turan AZ, Mert MS, Yüksel F, et al. Investigation of a novel & integrated simulation model for hydrogen production from lignocellulosic biomass. Int J Hydrogen Energy 2018;43(2):1081–93.
[182] Karatas H, Akgun F. Experimental results of gasification of walnut shell and pistachio shell in a bubbling fluidized bed gasifier under air and steam atmospheres. Fuel 2018;214:285–92.
[183] Basu P. Biomass gasification, pyrolysis and torrefaction practical design and theory. 2nd ed. New York: Elsevier; 2013.
[184] Jäger N, Conti R, Neumann J, Apfelbacher A, Daschner R, Bünder S, et al. Thermo-catalytic reforming of woody biomass. Energy Fuels 2016;30:7923–9.
[185] Marnellos GE, Athanasiou C, Makridis SS, Kikkinides ES. Integration of hydrogen energy technologies in autonomous power systems. In: Zoulias EI, Lymberopoulos N, editors. Hydrogen-based autonomous power systems. London: Springer-Verlag London Ltd; 2008. p. 23–81.
[186] Giddey S, Badwal SPS, Kulkarni A, Munnings C. A comprehensive review of direct carbon fuel cell technology. Prog Energy Comb Sci 2012;38(3):360–99.
[187] Gür TM. Critical review of carbon conversion in “carbon fuell cells”. Chem Rev 2013;113:6179–62076.
[188] Coa T, Huang K, Shi Y, Cai N. Recent advances in high-temperature carbon-air fuel cells. Energy Environ Sci 2017;10:460–90.
[189] Lee AC, Mitchell RE, Gur TM. Thermodynamic analysis of gasification-driven direct carbon fuel cells. J Power Sources 2009;194(2):774–85.