# Hydrogen Production for Improved Transportation System as a Part of Smart Cities

Volodymyr Tymofiiv, Samer Al-Rabeei(✉), Michal Hovanec, and Peter Korba

Faculty of Aeronautics, Department of Aviation Engineering, Technical University of Kosice, Rampová, 7041 21 Kosice, Slovakia
{Volodymyr.tymofiiv,Samer.al-rabeei,Michal.hovanec, Peter.korba}@tuke.sk

**Abstract.** The main purpose of hydrogen production is to move closer to industrial technologies and the development of a transportation system that will help to improve the future. Industrial hydrogen production is an integral part of hydrogen energy, the first link in the hydrogen consumption life cycle. Hydrogen is practically not present on Earth in pure form and must be extracted from other compounds using various chemical methods. There are currently many ways of industrially producing hydrogen. The diversity of hydrogen production methods is one of the main advantages of hydrogen energy, as it increases energy security and reduces dependence on certain types of raw materials. Efficient hydrogen production will help successfully by integrating the hydrogen infrastructure of the European "Smart cities" model, which globally supports the overall improvement of the environment. The peak power of conventional nuclear reactors or other power plants can also be used. The rapidly growing demand for hydrogen from refineries and chemical plants is the develop-ment of low-cost technologies. There are already limited networks of hydrogen pipe-lines that allow production facilities to be located at a certain distance from users. One approach to reducing the volatility of wind and solar electricity is to produce hydrogen by electrolysis and supply it to the gas network.

**Keywords:** Hydrogen technology · Hydrogen production · Production facilities

## 1 Introduction

One of the most important treaties governing the activities of individual states, international organizations and environmental NGOs is the Paris Agreement, adopted under the UN Framework Convention on Climate Change in 2015 and signed in 2016. The Paris Agreement emphasizes the need to combat global climate change by adapting economies in changing conditions and by increasing the attention paid to this problem [1].

The point of this Arrangement, in working on the execution of the Show, including its goal, is to fortify the worldwide reaction to the danger of environmental change with regards to reasonable turn of events and destitution annihilation endeavors, including:


D. Perakovic and L. Knapcikova (Eds.): FABULOUS 2022, LNICST 445, pp. 221–233, 2022.
https://doi.org/10.1007/978-3-031-15101-9_16

(a) Holding the increment in the worldwide normal temperature to well underneath 2 °C above pre-modern levels and seeking after endeavors to restrict the temperature increment to 1.5 °C above pre-modern levels, perceiving that this would essentially lessen the dangers and effects of environmental change.
(b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and
(c) Making finance streams predictable with a pathway towards low ozone harming substance emissions and environment strong turn of events [2]

In addition to increasing the portion of sustainable power sources in the energy balance, the following three areas will assume a significant part in achieving climate goals - the development of electric batteries, carbon catch, storage and storage (CCUS) technologies and hydrogen energy. At the same time, CCUS is seen as an intermediary in the transition to new energy, as these technologies will require the creation of a large-scale infrastructure. At the same time, batteries and hydrogen are part of the vision of the future in Europe and other countries that have committed themselves to reducing $CO_2$ emissions. Hydrogen use is estimated to potentially reduce up to 51% of global carbon dioxide emissions [3].

Hydrogen, as a fuel that does not leave a carbon footprint during combustion, can be a solution to critical problems for new energy based on renewable energy sources [4].

1. It can be a solution to the problem of uneven production of renewable energy sources. Excess volumes of electricity in the system will be directed at the peak to the production of hydrogen by electrolysis techno-logy, which will become a guaranteed source of energy during the period of low production of renewable energy sources.
2. Unlike electric batteries, hydrogen is ready to ensure the reliability of long-distance transport operations, which is particularly important for air and sea transport.
3. Widespread use of hydrogen can solve energy transport problems. Instead of building long electricity networks, renewable energy can be directed to the production of hydrogen, which can then be transported to other parts of the world using the current natural gas transport infrastructure.
4. Many industries cannot be decarbonised with the help of electricity, and hydrogen in this case can serve as a medium to achieve that goal [5].

## 2 Theoretical Part

Hydrogen - a colorless, flammable, odorless and unscented vaporous substance that is the least difficult individual from the group of synthetic components. The hydrogen iota has a core comprising of a proton and has a positive electric charge. An electron conveying a unit of negative electric charge is additionally associated with this core.

In any case, it happens in immense amounts as a feature of the water in the seas, ice sheets, streams, lakes and air. It creates a larger number of mixtures than some other component of the Mendelian table of occasional components. As a component of incalculable carbon compounds, he is available in all creature and plant tissues and in oil [6].

Hydrogen molecules $H_2$ are very small, so they can pass through very fine, invisible to the pores in bodies. Hydrogen has the lowest density of all chemical elements. One liter of hydrogen $H_2$ under normal conditions weighs 0.09 g, (density is 0.09 kg.m-3). It is highly flammable. Together with oxygen, it forms an explosive mixture. It burns with a light blue flame with a high temperature of up to 3,100 C.

Hydrogen gas easily forms covalent compounds - so most of the hydrogen on Earth exists in molecular compounds such as water. Many of them, like methane, are organic. There are technologies that allow the extraction of hydrogen from methane and water, which can then be transported and used [7, 8].

The interest in hydrogen as a source carrier can be explained by its high calorific value –120 MJ/kg, which is at least four times higher than coal (~10–30 MJ/kg) or twice higher than natural gas (~50–55 MJ/kg). Because carbon atoms are not involved in the combustion process, hydrogen is a carbon-free energy carrier. In addition, it can be saved. Due to properties such as the ability to store hydrogen, its high calorific value and the absence of $CO_2$ emissions from combustion, hydrogen is attractive for use in various energy sectors.

All solid (wood), liquid (petrol, diesel,…) and gaseous fuels (methane, propane,…) long chains of carbon (C) and hydrogen (H) atoms make up the materials we use today. Methane is the smallest of them, having only one carbon atom and four hydrogen atoms ($CH_4$). We use oxygen ($O_2$) to break the bonds between atoms, releasing the energy trapped inside those bonds. Because carbon and hydrogen atoms mix with oxygen atoms during combustion, we invariably produce carbon dioxide ($CO_2$) and water vapor ($H_2O$).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \Delta H = -890\,\mathrm{kJ/mol}\ \text{(exothermic reaction)}$$

There are not many gases that do not produce carbon dioxide when burned. And one of these gases, which can be completely independent of carbon, is hydrogen. It consists of two hydrogen atoms and does not form any carbon dioxide when reacted with oxygen [9].

$$[[2H]]_2 + O_2 \rightarrow 2H_2O \quad \Delta H = -286\,\mathrm{kJ/mol}\ \text{(exothermic reaction)}$$

It has many potential uses in many different areas of the economy. This can help decarbonise the production of energy consumed in transport, living space (especially heating) and industrial processes.

Not all industrial processes can be electrified and a carbon-neutral energy carrier is needed to fully decarbonise industrial production. Hydrogen is just one of the few substances that can be used for this purpose. Hydrogen and its derivatives are used in many industries, especially in the chemical and petroleum refining industries. Today, industry is the largest consumer of hydrogen. In all such examples, hydrogen can replace carbon processes.

Hydrogen is currently used in conjunction with oxygen in metal cutting, with a hydrogen-hydrogen flame having a temperature of up to about 3000 °C. It is also used as fuel for space shuttle rockets. In the chemical industry, this element is used for the production of important chemicals such as HCl, $NH_3$ (ammonia) or in the hardening of vegetable oils [10].

## 2.1 Differences in the Understanding of the Label

Hydrogen also can be produced using a different of sources and several different methods. The main sources for its production are divided into two groups: production from fossil fuels (natural gas, coal, heavy gasoline and other hydrocarbons) and production from renewable energy sources. Fossil fuels can be converted to production using various technological processes, generally classified as thermochemical, biochemical and photochemical conversion. Among these processes, the most common is steam reforming of methane and is currently used for most of the global hydrogen production [11].

Hydrogen can be classified depending on the source and method of production, and so far the main system of hydrogen classification is color classification (Table 1).

**Brown and Black: Coal Gasification**

The earliest method of producing hydrogen is to convert coal to gas. Gasification converts carbon monoxide, hydrogen, and carbon dioxide from organic carbonaceous compounds derived from fossil fuels. Gasification takes place at extremely high temperatures (more than 700 °C), with a controlled amount of oxygen or steam, and without combustion. Carbon monoxide is then converted to carbon dioxide and hydrogen by reacting with water.

Coal gasification is the reaction of carbon with water vapor or oxygen, resp. Both. Coal gasification principle: The basis is an endothermic reaction [12].

$$C(solid) + H_2O \rightarrow CO(gas) + H_2O$$

Gray color: steam reforming.

The majority of hydrogen nowadays comes from natural gas; it is carbon-bound and can be separated from it using a water-based process known as steam reforming. However, $CO_2$ is produced by the excess carbon synthesized in the prophesy. Gray hydrogen now accounts for the majority of production, emitting 9.3 kg of $CO_2$ per kilogram of hydrogen produced. When hydrogen is referred to be "gray," it signifies that it was created from fossil fuels without collecting greenhouse gases, and that the only difference between it and brown or black hydrogen is a minor quantity of emissions produced during the process.

The basis of the natural gas process of steam reforming is the reaction of methane with water: [13].

$$[[CH]]_4 + H_2O\,(\rightarrow \perp(1000\,°C))\ CO + [[3H]]_2\ \ \Delta H = 203\,kJ/mol\ \ (endothermic\ reaction)$$

$$CO + H_2O \rightarrow [[CO]]_2 + H_2 \quad \Delta H = -41\,kJ/mol\ \ (exothermic\ reaction)$$

Blue: steam reforming using CCUS / CCS.

Blue hydrogen is mostly made from natural gas via a method known as steam reforming, which involves combining natural gas with heated water to make steam. Hydrogen and carbon dioxide are produced, with the latter being recovered in industrial carbon capture, utilization, and storage (CCUS) systems. By transferring trapped $CO_2$ into underground cavities, such as recovered gas and oil deposits, or finding industrial uses for the trapped gas, CCUS programs aim to make blue hydro-gen production climate-neutral. However, because the technique does not actually prevent the generation of greenhouse gases, blue hydrogen is best described as "low $CO_2$ hydrogen" [14].

Turquoise color: pyrolysis of methane.

The method of obtaining natural-gas-derived hydrogen is currently in the experimental phase. The natural gas can decompose at too high temperatures to form hydrogen and solid-carbon due to a process named pyrolysis of methane. This hydrogen is called "turquoise" or "low carbon" hydrogen. Turquoise hydrogen has a low carbon footprint because carbon may be buried or employed in industrial processes like steelmaking or battery manufacturing to prevent it from escaping into the atmosphere.

Pyrolysis of methane (or cracking of methane) is a chemical process that breaks down methane or hydrocarbons in general into its elemental components: hydrogen and solid carbon. The reaction is endothermic [15].

$$[[CH]]_4 \rightarrow C\,(\text{solid}) + 2H_2 \quad \Delta H = 74,52\ \text{kJ/mol (endothermic reaction)}$$

Green color: electrolysis supplied by electricity from revivable energy sources.

Green hydrogen is produced from revivable electricity with the help of electrolysis. Electrolyzers split water into hydrogen and oxygen components using an electrochemical reaction that produces no carbon dioxide. Although hydrocarbons are currently the main feedstock used to produce hydrogen, the share of low-emission hydrogen is expected to increase in the long term and to dominate conventional technologies [16].

Water electrolysis is a physico-chemical process in which distilled water decomposes into oxygen and hydrogen by the action of a direct current. Due to the division of water molecules into parts, hydrogen and oxygen are formed in a ratio of 2: 1 [17].

$$H_2O + \text{electricity} \rightarrow H_2 + 0,5\ O_2$$

Pink color: electrolysis supplied by electricity from nuclear energy.

Pink is often used for hydrogen ginned by electrolysis using nuclear-energy. Nuclear energy is a very versatile technology and provides low-carbon electricity that can be used to produce pure hydrogen [18].

**Table 1.** Hydrogen classification

| Color | | Production source | Production technology |
|---|---|---|---|
| Gray | | Natural gas | Most commonly through steam reforming from natural gas |
| Blue | | Natural gas | Most commonly through steam reforming from natural gas along with the use of CCS technology |
| Turquoise | | Natural gas | Pyrolysis of methane |
| Brown or black | | Coal | Gasification |
| Green | | Electricity from RES | Water electrolysis |
| Purple or pink | | Electricity from nuclear power plants | Water electrolysis |

## 3 Analytical Part. Global Use of Hydrogen Today and in the Future

At present, almost all hydrogen use is concentrated in industry. The four main uses of hydrogen currently are: oil refining (37 Mt/year), ammonia production (31 Mt/year), methanol production (13 Mt/year) and steel production by direct reduction of iron ore (5 Mt/year) (Fig. 1.). Almost of hydrogen comes from fossil fuels. [19] This current utilization of hydrogen is the premise of numerous parts of the worldwide economy and our regular routines. Their future development relies upon the improvement of interest for downstream items, in particular refined transport fuels, food fertilizers and building materials [20].

Interest for ammonia and methanol is expected to growing in the short to medium term, with the addition of new capacity providing relevant opportunity to expand the use of low-emission hydrogen routes. Efficiency gains can reduce the overall level of demand, but this will only partially offset the growth in demand. Regardless of whether it's petroleum gas with CCUS or electrolysis, the innovation is accessible to help the extra hydrogen request development anticipated for alkali and methanol will essentially assist with lessening outflows [21].

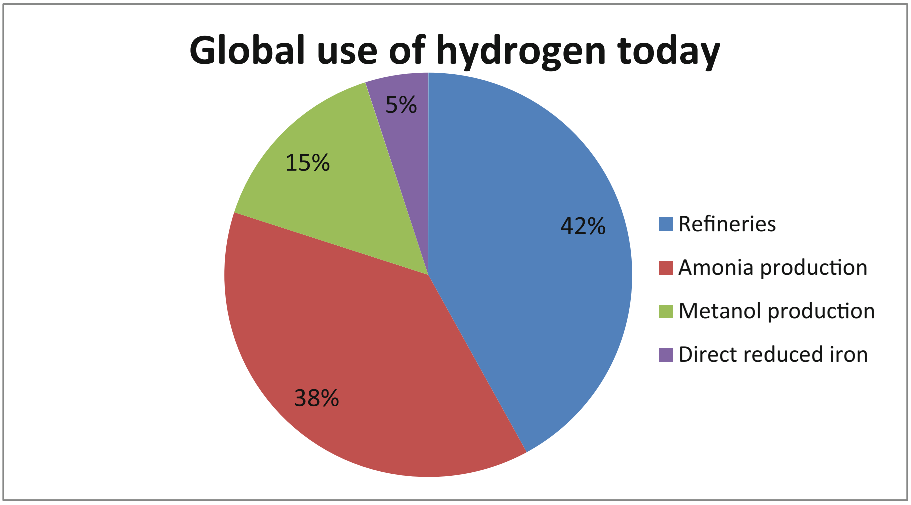


**Fig. 1.** Global use of hydrogen today. Source: IEA, Worldwide hydrogen interest by area in the Net Zero Situation, 2020–2030

In the long term, steel and high-temperature heat generation offers enormous potential for increased demand for low emission hydrogen. Currently, there are technological problems that are preventing widespread adoption of hydrogen in these areas, reducing costs and scaling up. In the long term, it should be technically possible to produce all primary steel with hydrogen, but this will require huge amounts of electricity with low carbon content (about 2500 TWh/year, or about 10% of the world's electricity production today) [22].

Hydrogen has likewise since a long time ago been known as a potential low-carbon transport fuel, yet it has been hard to fuse it into the vehicle fuel blend [23].

However, by 2030, hydrogen use in the various modes of transport is expected to be 8.55 Mt per year. In addition, ammonia is expected to be used as a fuel for ships, and by 2030 about 18 Mt of hydrogen will be needed to make it known (Fig. 2) [24].

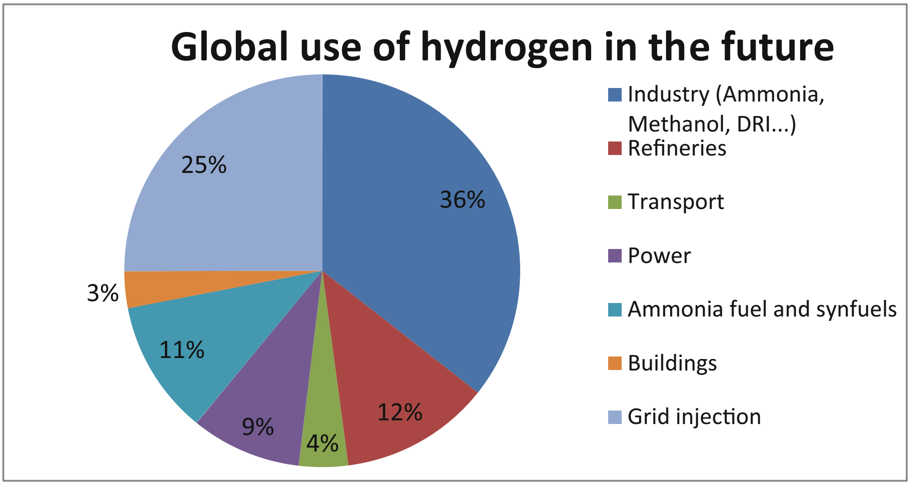


**Fig. 2.** Estimated global use of hydrogen in the future. Source: IEA, Worldwide hydrogen interest by area in the Net Zero Situation, 2020–2030

## 4 Practical Part- Comparison of Hydrogen Production Methods

Hydrogen demand in 2020 was ~90 Mt. Of this total hydrogen produced, 70 Mt was produced from fossil fuels and 19 Mt as a by-product in refineries and 0.5 Mt of hydrogen was produced using electrolysers. In the future, the share of "gray" hydrogen from fossil fuels, an increase in the share of low-emission "blue" hydrogen and a huge increase in "green" hydrogen are expected. In 2030, hydrogen production by electrolysis should reach 75–80 Mt and become the leading technology in the hydrogen production market. In general, the market for hydrogen production in 2030 should be around 210 Mt per year (Fig. 3) [25].

**Costs**

The cost of hydrogen gas is determined by the cost of raw materials and energy, as well as by the method of production. When hydrogen is produced from natural fuels, its costs depend linearly on the cost of the raw materials. In the electrolytic method of hydrogen production, its price depends on the cost of electricity by 70–90%, which means that the cost of hydrogen is affected by the parameters of the electrolyser and the price of electricity [26].

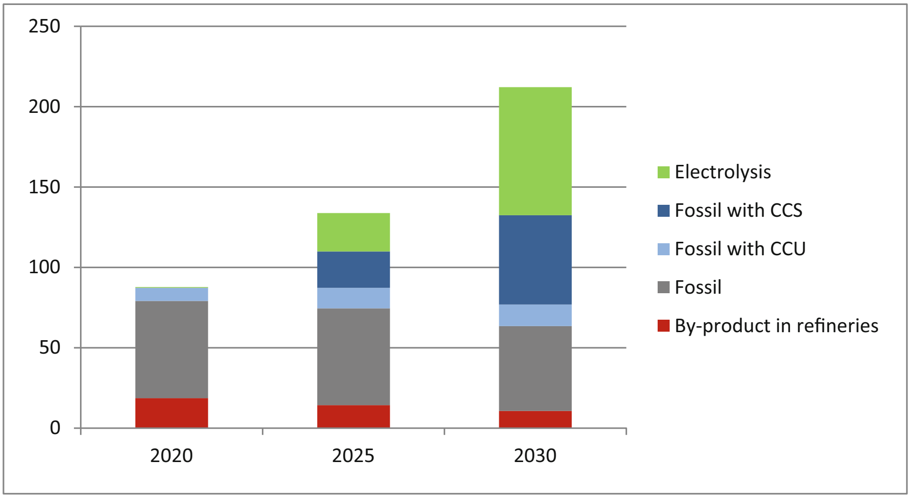


**Fig. 3.** Global hydrogen demand by production technology in the Net Zero Scenario, 2020–2030. Source: IEA, Hydrogen. Tracking report

Gray hydrogen is currently the cheapest option at around € 1 per kg, but in some regions it is as high as $ 3 per kg. For China and India, which import most of their gas, coal-based hydrogen is generally the cheapest option. If CCS technology is used to convert the cheapest gray hydrogen to blue, this will lead to a cost of around € 1.5 per kg (Table 2) [27].

**Table 2.** Cost of 1 kg of commercial hydrogen.

| Hydrogen production process | Energy source | Efficiency, % | Cost, EUR / kg |
|---|---|---|---|
| Steam reforming | Natural gas | 60–75 | 0,9–3.2 |
| Steam reforming with CCUS | Natural gas | 55–70 | 1,5–2,9 |
| Gasification | Coal | 60–80 | 1,2–2,2 |
| Electrolysis | Renewables | 35–45 | 3–7,5 |

Source: IEA

The most difficult aspect of hydrogen production, particularly from renewable sources, is supplying hydrogen at a lower cost. This means that the cost of hydro-gen must be less than € 4 per gallon of petrol equivalent, regardless of production technology. Research aims to increase the efficiency and longevity of hydrogen production technologies, as well as lower capital equipment, operation, and maintenance expenses, in order to lower the total price of hydrogen [28, 29].

## Emissions

Greenhouse gas emissions from hydrogen production differ depending on the technology (Fig. 4). Hydrogen produced from fossil fuels isn't always clean exhibit the highest $CO_2$ emissions. Using natural gas or coal to generate electricity for electrolysis can result in a higher $CO_2$ intensity than gray or blue hydrogen due to conversion losses during power generation. If CCUS is used, hydrogen derived from natural gas with CCUS represents the lowest $CO_2$ intensity after hydrogen obtained from renewable or nuclear power, and the higher rate of capture of CCUS, the lower the $CO_2$ intensity of blue hydrogen [30].

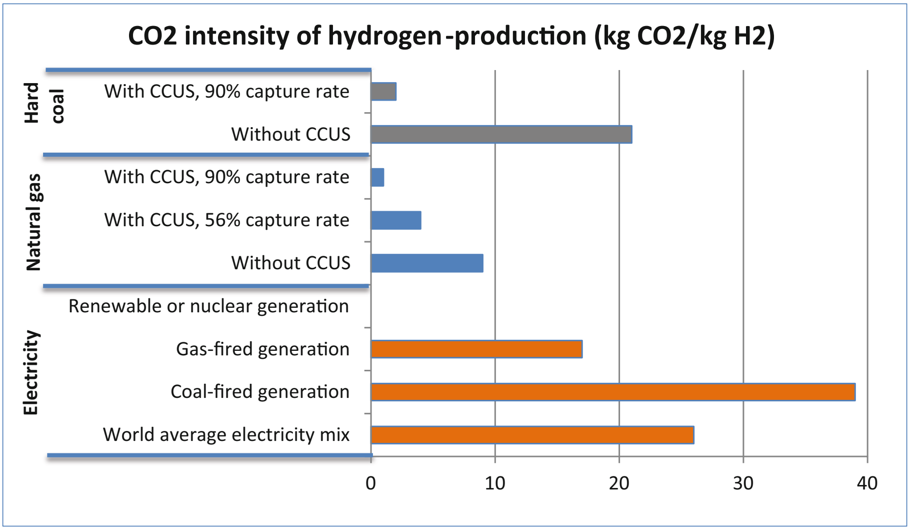


**Fig. 4.** $CO_2$ intensity of hydrogen production Source: IEA (2019)

Not only is it important to know how hydrogen is made, but also whether it is made on-site or off-site, leads to greater $CO_2$ emissions as $CO_2$ is released during the supply, storage and filling of hydrogen. When the same manufacturing technology is used, the off-plant hydrogen production process increases the $CO_2$ intensity as on-site cases. Different modes of hydrogen transport also result in different $CO_2$ emissions. The transport of compressed hydrogen is less carbon-intensive than the transport of liquefied hydrogen [31].

## Possibilities of Using Hydrogen in Smart City

If we talk about the introduction of hydrogen into the SMART CITY model, then it is worth immediately noticing its several obvious advantages. When used with fuel cells, only water vapor is created instead of various greenhouse gases and microparticles. This feature of hydrogen has huge potential to prevent smog in car-crowded cities and to prevent huge $CO_2$ emissions from industry.

In addition, hydrogen is a universal energy carrier and a universal energy storage.

At the moment, 3 main sources of energy play the main role in cities: electricity, natural gas and petroleum products (gasoline and diesel). And just the same, hydrogen can combine these 3 energy sources or become a link connecting them. For example, it can be used to heat houses (instead of natural gas) and fill cars with it (instead of gasoline). That is, to influence those industries where there is not always the possibility of electrification. Also, in the event of a shortage of one of these sources, it will be possible to easily convert part of the electrical energy into hydrogen and increase the share of its use, for example, for heating [32, 33].

## 5 Conclusion

Hydrogen production advancements are in different transformative phases. A few advancements, for example, steam methane changing, are as of now business and can be utilized soon. Others, for example, sun oriented thermochemical water parting, photo electrochemical and organic, are in the beginning phases of research facility advancement and are viewed as possible pathways in the long haul.

The two main markets for hydrogen consumption today are ammonia and methanol production, but in the future hydrogen will be used for different purposes and in different sectors. Hydrogen demand in the oil refining industry is also expected to increase. Now 95% of the hydrogen produced is used by consumers for their own use and only 5% of it has been sold commercially on the market. The amount of free hydrogen on the market is likely to increase in the future.

In a conservative scenario of growing industrial hydrogen consumption, its share will increase from 70 million to 230 million tons per year by 2050. The share of commercial hydrogen will also increase, from 4 million to 140 million tons per year.

For example, to produce 140 million tonnes of hydrogen per year by 2050, HTGR power units with a total heat capacity of 400 GW should be built worldwide.

## References

1. LNCS Homepage (2016). http://www.springer.com/lncs
2. United Nations, Framework Convention on Climate Change, Distr.: Limited 12 (2015). https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
3. United Nations, Paris Agreement, Article 2, (2015). https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf
4. Rystad Energy Transition Report, Hydrogen Society, February (2021). http://petrodin.com/data/documents/2021-RYSTAD-Energy-Transition-Report.pdf
5. Tashie-Lewis, B.C., Nnabuife, S.G.: Hydrogen production, distribution, storage and power conversion in a hydrogen economy - a technology review. Chem. Eng. J. Adv. (2015). https://www.sciencedirect.com/science/article/pii/S2666821121000880. ISSN 2666-8211
6. Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W.R.: Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. Appl. Energy **266**, 114848 (2020). https://doi.org/10.1016/j.apenergy.2020.114848. ISSN 0306-2619
7. Universal Industrial Gases, Inc., Hydrogen ($H_2$) Applications and Uses, 15 September 2005

8. Ma, Y., Wang, X.R., Li, T., Zhang, J., Gao, J., Sun, Z.Y.: Hydrogen and ethanol: production, storage, and transportation. Int. J. Hydrogen Energy, **46**(54), 27330–27348 (2021). https://www.sciencedirect.com/science/article/pii/S0360319921021777. ISSN 0360-3199
9. Karuskevich, M., Ignatovich, S., Karuskevich, O., Maslak, T., Pejkowski, L., Kurdel, P.: Fatigue and overstress indicators for ultralight and light aircraft. Fatigue Fract. Eng. Mater. Struct.: FFEMS **44**(2), 595–598 (2021). ISSN 8756-758X
10. Scott, K.: Chapter 1: Introduction to electrolysis, electrolysers and hydrogen production. RSC Energy Environ Series, vol. 2020, no. 25, pp. 1–27 (2020)
11. Danish Energy Agency and Energinet, Technology Data – Renewable fuels (2017). http://www.ens.dk/teknologikatalog
12. Pareek, A., Dom, R., Gupta, J., Chandran, J., Adepu, V., Borse, P.H.: Insights into renewable hydrogen energy: recent advances and prospects. Mater. Sci. Energy Technol. (2020).https://www.sciencedirect.com/science/article/pii/S258929912030001X. ISSN 2589-2991
13. Marimuthu, S., Chinnathambi, D.: Computational analysis to enhance the compressible flow over an aerofoil surface. Aircr. Eng. Aerosp. Technol. **93**(5), 925–934 (2021)
14. Song, C., Liu, Q., Ji, N., Kansha, Y., Tsutsumi, A.: Optimization of steam methane reforming coupled with pressure swing adsorption hydrogen production process by heat integration. Appl. Energy (2015).https://www.sciencedirect.com/science/article/pii/S0306261915006480. ISSN 0306-2619
15. Soltani, S.M., Lahiri, A., Bahzad, H., Clough, P., Gorbounov, M., Yan, Y.: Sorption-enhanced Steam Methane Reforming for Combined CO2 capture and hydrogen production: a state-of-the-art review. Carbon Capture Sci. Technol. (2021).https://www.sciencedirect.com/science/article/pii/S2772656821000038. ISSN 2772-6568
16. Schneider, S., Bajohr, S., Graf, F., Kolb, T.: State of the art of hydrogen production via pyrolysis of natural gas (2020)
17. Yuvaraj, A.L., Daniel, S.: A systematic study on electrolytic production of hydrogen gas by using graphite as electrode. Mater. Res. **17**, 83–87 (2014)
18. Bermudez, J.M., Hannula, I.: Hydrogen. Tracking report (2021). https://www.iea.org/reports/hydrogen
19. IEA Publications, The Future of Hydrogen, Japan (2019). https://www.capenergies.fr/wp-content/uploads/2019/07/the_future_of_hydrogen.pdf
20. Šváb, P., Korba, P., Hovanec, M., Ukáč, J., Hura, J., Al-Rabeei, S.: The Utilization of renewable energy sources in the construction and maintenance of transport infrastructure. In: Future Access Enablers for Ubiquitous and Intelligent Infrastructures: 5th EAI International Conference. Springer, Cham, pp. 362–373 (2021). https://link.springer.com/content/pdf/10.1007%2F978-3-030-78459-1.pdf. ISBN 978-3-030-78458-4
21. Acar, C., Dincer, I.: Comparative assessment of hydrogen production methods from renewable and non-renewable sources. Int. J. Hydrogen Energy **39** (2014). https://www.sciencedirect.com/science/article/pii/S0360319913025330. ISSN 0360-3199
22. Kumar, R., Joshi, S., Awasthi, S.: An intelligent system for audio emotion recognition. Int. J. Adv. Sci. Technol. (2019)
23. Bičáková, O., Straka, P.: Production of hydrogen from renewable resources and its effectiveness. Int. J. Hydrogen Energy **37**(16), 11563–11578 (2012)
24. Reigstad, G.A., Coussy, P., Straus, J., Bordin, C.: Hydrogen for Europe Final report of the pre-study. SINTEF Energy Research 22 08 2019 (2019).https://www.sintef.no/globalassets/sintef-energi/hydrogen-for-europe/hydrogen-for-europe-pre-study-report-version-4_med-omslag-2019-08-23.pdf
25. Shibata, Y., Matsumoto, T., Kan, S.: Institute of energy economics, Japan, clean hydrogen: important aspects of production. International Cooperation, and Certification. Part 2, Tokyo/Wuppertal (2020). http://www.gjetc.org/wp-content/uploads/2020/07/GJETC_Hydrogen-Society-Study-II.pdf

26. Al-Rabeei, S.A.S., Korba, P., Hovanec, M., Šváb, P., Rácek, B., Spodniak, M.: Analysis of aviation pollution in the selected regions of the world. In: Perakovic, D., Knapcikova, L. (eds.) Future Access Enablers for Ubiquitous and Intelligent Infrastructures. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol. 382, pp. 229–239. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-78459-1_17
27. Hydrogen Council, McKinsey & Company, Hydrogen Insights Report (2021). https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf
28. Han, W., et al.: Simultaneous dark fermentative hydrogen and ethanol production from waste bread in a mixed packed tank reactor. J. Clean. Prod. **141**, 608–611 (2017)
29. Burhan, M., Shahzad, M.W., Choon, N.K.: Hydrogen at the Rooftop: compact CPV-hydrogen system to convert sunlight to hydrogen. Appl. Therm. Eng. (2017)
30. Balat, M.: Potential importance of hydrogen as a future solution to environmental and transportation problems. Sila Science & Energy Unlimited Company (2008)
31. Dincer, I., Rosen, M.A.: Sustainability aspects of hydrogen and fuel cell systems. Faculty of Engineering and Applied Science, University of Ontario Institute of Technology (2000)
32. Rohacs, J., Kale, U., Rohacs, D.: Radically new solutions for reducing the energy use by future aircraft and their operations. Energy **239**, 122420 (2022). https://doi.org/10.1016/j.energy.2021.122420. ISSN 0360–5442
33. Bossel, U., Eliasson, B.: Energy and the Hydrogen Economy, Oberrohrdorf, Switzerland (2003)