Methodology for choosing a hydrogen source based on a point system

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Abstract. The article examines the usage of hydrogen in gas transmission pipes as one of the measures to achieve the criteria of sustainable development and reduction of carbon emissions. Regarding choosing an appropriate kind, hydrogen sources have been analyzed. Due to the multifactorial nature of the task, such as raw material, price, efficiency, popularity, and the availability of many studies, a point system was developed to evaluate the alternatives with significant criteria. On its basis, it was established that the cheapest and gentlest natural method is the electrolysis of water. For this purpose, electrolysis methods have been evaluated, and efficiency depends on the energy source. Given the dependence of the price of energy on the country's energy mix, a point system is proposed based on the parameters: hydrogen's levelized cost LCOH and levelized cost of electricity (LCOE). The newest criterion is the citation rating which gives popularity and an opportunity for new research.

1 Introduction

Overcoming the global warming trend is related to introducing measures to reduce carbon emissions. It is predicted that by 2030 they will decrease by 45%, and by 2050 there will be none [1]. Measures to reduce them are diverse, including renewable energy production, increasing energy and production efficiency, producing pollution-free products, carbon capture and processing, reuse and recycling of solid, liquid, and gaseous materials, online communication with a reduced amount of paper, mobility through wireless technologies, rehabilitation of buildings, management in all spheres of life according to the criteria of sustainable development, recording and reporting of the status, certification of processes and products, planting trees and others [2-5]. It is expected that after an analysis of the collected data, new measures to reduce carbon emissions will be indicated.

A new trend is imposing an opportunity to replace natural gas with hydrogen fuel. Hydrogen is known to be a clean energy carrier. It releases energy with high efficiency through an electro-oxidation reaction in a fuel cell to generate only one product: water. They do not emit carbon emissions, i.e. this is a clean method. It is recommended that it be produced using efficient technologies that also have no carbon footprint. The use of hydrogen is related to its injection into the pipeline network and the establishment of its

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concentrations in various facilities. Depending on the parameters of the pipeline network and consumers, the percentage of hydrogen can vary from 5 to 50% [6]. To increase security and comply with European directives, quantities should be tracked through a digitized system [7]. Regulatory bodies recommend IoT, edge computing, blockchain, AI, machine learning, ERP, 5G, cloud computing, and others [8-10]. On the one hand, the introduction of digitization from the Industry 4.0 segment is associated with the need to invest funds [11]. Still, on the other hand, the ability to track material flows increases security and enables analysis. Not a small motivation for digitized tracking and analysis of parameters is the possibility to correct management impacts, increase trust between partners, and ultimately satisfy the wishes and expectations of government and regulatory authorities, private and public companies, and, last but not least, citizens for use of hydrogen produced without a carbon footprint.

To address this question, the challenges to implementing hydrogen in pipelines must be determined. First of all, it is the source of raw material. In most cases, it is produced by various methods that vary widely in efficiency and cost [12-15]. Next, determine the parameters and concentrations of hydrogen injection into the network, including its compressibility and the Wobbe characteristic [16-18]. Last but not least is the expected economic effect, i.e. the return on investment, determining the price of the devices, and the possibility of technical support and repair [19]. In this aspect, the need for qualified personnel to not only serve but also manage the gas transmission network should also be addressed.

This task is quite complex due to the presence of heterogeneous factors. Therefore, the team is tasked with developing a point assessment to determine the appropriate and technically economically relevant alternatives for selecting a suitable hydrogen source.

Considering the need to reduce the carbon footprint, the types of hydrogen are considered according to the way of their production, i.e. according to their categorization in terms of carbon emissions released during their production.

2 Types of hydrogen

Depending on the production method, different types of hydrogen are differentiated and they are [14, 15, 19]:

- aqua - from oil sands, an experimental method with no carbon footprint;
- white is extracted from nature in gaseous form;
- green, produced using electricity from clean energy sources;
- pink by electrolysis from (nuclear energy from RES);
- blue, produced like grey but with carbon capture and storage (CCS or CCUS);
- yellow – electrolysis, but the energy is from mixed sources;
- red by gasification of biomass with carbon capture or not;
- grey, brown, and black - produced from gas, brown, and black coal with the highest level of carbon emissions, obtained by methane conversion and coal gasification;
- turquoise hydrogen by methane pyrolysis with solid carbon waste.

Table 1 summarizes the costs of hydrogen by color, and it can be seen that the cheapest method for hydrogen production is the use of natural gas [19]. Figure 1 shows the distribution of costs by color of hydrogen, according to its production. It shows additionally that the processing of natural gas is the cheapest method.

Due to a requirement to reduce the carbon footprint is necessary to ignore the low cost and the higher efficiency at the processing of the fossil fuels. This means, to look in detail, at the conversion methods. Their importance for the achievement of compatibility with the sustainable development criteria depends on the energy used for their extraction, the installed technological lines for capturing carbon dioxide, and the efficiency of the described processes. The classification made is not the most accurate but gives an approximate order for the environmental compatibility.

Table 1. Costs for hydrogen production by colors.

USD/kgH$_2$		Hydrogen color	Source
2.28	7.39	green	water electrolysis based on RES
3.56	5.46	purple, pink, red	water electrolysis based on nuclear
4.83	13.11	yellow	electricity from an energy mix
0.67	1.31	grey	natural gas
2	2.6	turquoise	pyrolysis of methane
0.99	1.83	blue	natural gas with CO_2 capture
1.6	2.05	blue	coal
1.6	3	brown	biomass
1.2	2	black	coal

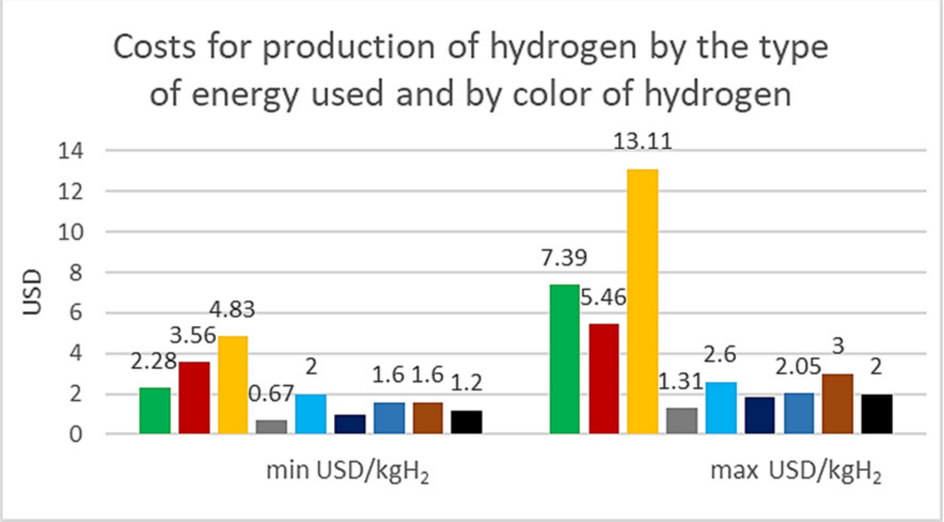

Fig. 1. Costs of hydrogen production, by types of energy source and color of hydrogen, from minimum to maximum value.

The existence of heterogeneous publications and measurements on the subject makes the comparison of the alternatives difficult. That is why solving this multi-criteria problem is possible by point methods. The point assessment offered in this case is appropriate because the methods are evaluated on numerous factors, have different costs, production capabilities, even significance by geographical location, etc. In some regions, certain raw materials may be used, for example, white hydrogen as a raw material for extraction [13]. In other cases, a certain species is an alternative in some areas, while it is recommended to avoid others. For example, pink hydrogen is generated by a high-temperature catalytic water-splitting process, using nuclear thermal energy, which is not tolerated by the EU, but is a practical alternative for China and Russia [20].

3 Application of point system

Point systems are an ideal method for evaluating heterogeneous data in the absence of sufficient information in a short period. They are used in various fields of engineering sciences, education, medicine, and others for a multi-criteria task, if necessary to evaluate systems with the synergistic influence of parameters of production, environment, and economic efficiency. To realize a successful process, it is necessary to review a few documents, but at the same time actively discuss with a group of experts who are specialists in the studied areas. The application of this decision-making method cannot be very accurate if the procedure is not carefully designed [21]. The point systems are not final, but they are leading to determine the directions for the development of a research or decision [21, 22]. When developing the system, it is important that the points for the individual criteria are expressed in the form of uncertain linguistic information, each receiving a weight according to its impact on the particular study [22]. The determination of severity should be based on data from actual measurements or process observations.

Therefore, when developing the proposed point system, the team established various important criteria such as the level of carbon emissions according to the type of source, cost, energy, and efficiency. Unfortunately, the data in the literature are heterogeneous.

A detailed point system has been made to evaluate hydrogen production methods based on energy efficiency, Exergy efficiency, efficiency, price per kilogram of hydrogen, Production cost (US$/kg H_2), carbon and Acidification potential (g SO_x/kg H_2), Technology maturity level [23]. The detailed examination of the methods is not based on the regional characteristics that determine the type of available raw materials, their price, the influence of the country's energy mix on the final price, the availability of renewable energy sources, and others. The detailed system makes it difficult for users. It lacks an emphasis on the trend of development and maturity of the technology, which is expressed in the number of citations for recent years. The latter factors are an advantage of the methodology proposed by the team in this paper. By dividing the main methods into sub-methods, it is possible to choose the appropriate step by step.

Therefore, the solution is to look at the main known methods and choose one of them according to the points the best alternative. To do this with all methods and then to analyze them according to the following criteria:

- Hydrogen source;
- Hydrogen production methods;
- Evaluation of a method according to the carbon footprint;
- Evaluation of a method according to the price per kilogram of hydrogen;
- Evaluation according to the final price;
- Evaluation of a method according to effectiveness.

4 Hydrogen production methods

Hydrogen can be generated chemically, through reforming, hydrolysis, gasification of fuels, and others, using various feedstocks [14, 19, 23-27]:

- lectrolysis of water;
- the plasma reforming method [28];
- water separation process;
- photolysis (photoelectrolysis);
- reforming and cracking of natural gas;
- oil and production from fossil fuels;
- high-temperature electrolysis from biomass;
- coal gasification;

• extraction from natural sources;
• other methods.

Hydrogen production using crude fossil fuels results in carbon-intensive emissions of 12-13 kg CO_2-eq/kg H_2. According to the announced commitments (APS), emissions should fall to 3 kg CO_2-eq/kg H_2 by 2050, and according to Net Zero by 2050 reach below 1 kg CO_2-eq/kg H_2. Their quantity decreases when using green energy or to values of 0.8-4.6 kg CO_2-eq/kg H_2 for partial oxidation of natural gas with carbon capture and storage (CCS). Gas processing with carbon capture and storage achieves 0.7 kg CO_2-eq/kg H_2 (capture rate 93%), increasing total emissions to 1.5-6.2 kg CO_2-eq/kg H_2 when the upper and lower bounds on global emissions are included up and in the middle for natural gas supplies today. Crude coal processing generates 24 kg CO_2-eq/kg H_2. Using green electricity is one of the purest technologies that generating to 0.5 kg CO_2-eq/kg H_2 for Sweden, which has one of the lowest emission factors for grid electricity production in the world today (10 g CO_2-eq/kWh).

Depending on the type of electricity, average levels have been set for Nuclear electricity - 0.1-0.3 kg CO_2-eq/kg H_2. Wind, solar PV, hydro, and geothermal have zero upstream and direct emissions [29]. Naturally, the amount depends on the energy mix of the country and the raw material (Figure 2).

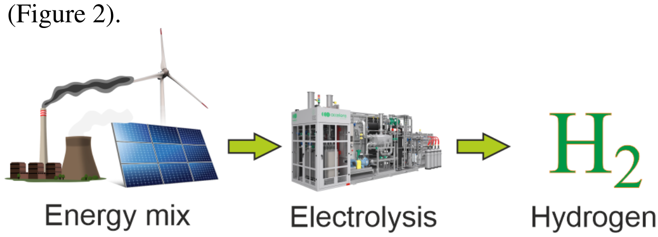

Fig. 2. Hydrogen production, powered by energy from renewable and conventional sources.

4.1 Methods

In the next point, the main characteristics and raw materials for hydrogen extraction according to the different methods are indicated.

Plasma reforming. The feedstock is methane, which is converted by reaction with CO_2 and H_2O. The main processes are steam reforming, dry reforming, and partial oxidation [24]. The first two processes are endothermic, but the third is an exothermic reaction with decreasing energy. The first of them is used in over 90% of industrial hydrogen production facilities [25]. Methane conversion in a plasma reactor with a three-phase high-voltage plasma torch has power parameters of 80–120 kW, levels (91–98.3%), and low energy consumption of 31.8–35.9 MJ per 1 kg. DC arc vapor plasma parameters are levels of 49–74% with energy consumption of 18–28.4 kWh/kg. Nitrogen reforming shows 9.6 kW, levels of 92.32-82.19%, and the required energy is 290 kJ/mol.

Dry reforming - Conversion is up to 99.5%, H_2 selectivity is up to 99.9%, and the energy of 1 mol of hydrogen is 158 kJ/mol.

The energy required to produce 1 kg of hydrogen is 79 MJ/kg (Steam reforming), 116 MJ/kg (Dry reforming), 192 MJ/kg (Steam reforming-plasma torch), and 166 MJ/kg for hydrogen produced from water electrolysis [28].

Steam Plasma Methane Reforming for Hydrogen Production. Reforming natural gas - various alternatives are possible. Methane can be converted to H_2 or syngas by steam methane reforming, dry methane reforming, and partial methane oxidation. The method generates a carbon footprint. Thermolysis is chemical decomposition by heating water without carbon emissions. It is considered one of the most environmentally friendly methods, as the efficiency increases with the increase in the number of temperature increase cycles.

Biophotolysis. Biophotolysis also uses water as a source to dissociate water molecules by low-throughput methods. Products are hydrogen and oxygen in biological organisms under the influence of solar radiation. Requires sunlight and a large reactor.

Pyrolysis. Biomass pyrolysis produces hydrogen based on hydrolysis, combustion, gasification, and fermentation. He considers it one of the most convenient and economical methods of hydrogen production. Biomass gasification has a higher conversion efficiency due to the higher calorific value of the product gases (CO, H_2, and CH_4), easy oxidation and high annual productivity. The efficiency is optimal at a temperature of 700–1200 °C, oxygen, air, steam or their combination as the gasifying agent [25].

Fermentation. Dark fermentation (DF) of hydrogen also uses organic biomass to produce hydrogen from anaerobic bacteria. The substrate should be rich in carbohydrates or dark. It is characterized by a high net energy coefficient of 1.9.

Photofermentation uses solar energy and therefore the potential depends on the range of sunlight. The process also depends on the quality of the substrate and the H_2 production methods with waste disposal.

Photocatalysis is a promising way to efficiently convert and store solar energy.

Thermochemical. Hybrid thermochemical cycles use heat and a little electricity at the same time to produce hydrogen from water. Their advantage is the established lower consumption of electricity than electrolysis. Second, they have lower temperature and heat requirements than thermal water splitting. A disadvantage is the presence of a SO_3 reduction temperature and the application of corrosive chemicals.

Gasification. Coal gasification is considered to be the most cost-effective method due to its high calorific value. Another effective method is partial oxidation of coal at high pressure, approximately 5 MPa [25]. Both methods have high carbon emissions.

Photosynthesis. Artificial photosynthesis is the biochemical reaction that mimics natural photosynthesis. It has low efficiency of light capture, electron transfer, water splitting, and CO_2 reduction, and high cost.

Hydrolysis. Regarding the hydrolysis methods discussed above and the use of different types of chemical reactions for hydrogen production, the following conclusions are drawn, from the point of view of the processes with the lowest environmental pollution and the best use of the generation possibilities:

- Processes directly related to the generation of hydrogen are the most efficient;
- Processes generating hydrogen with electricity are also highly efficient, due to the fact that no emissions are released into the atmosphere;
- The use of RES leads to higher efficiency compared to other energy sources;
- In terms of costs, the most effective are the processes associated with the lowest capital costs – electrolysis of water.

The energy intensity of the process as a factor should not be underestimated. With him, the least energy-intensive processes are valued the most.

4.2 The proposed point system

Table 2 evaluates the production methods according to the criteria of cost, efficiency, amount of carbon emissions, capital costs, and citability. Scores range from 1 to 10, with a higher value indicating better performance. From Table 2 can be seen that papers related to electrolysis have many citations. Similarly, the citations of hydrogen pyrolysis studies also have many citations, as can be seen from Figure 3.

From Table 3 can be seen that hydrogen production processes could be assessed, according to their efficiency. Based on the considered methods, it is established that electrolyzers are the most ecological way of hydrogen production. Moreover, they can be built anywhere, using water as a source. Their effectiveness depends solely on the type of electrolyzer and the energy used. For this reason, a point assessment of the main electrolyzers will be made.

Table 2. Point system for different kind of method's productions.

Method	H_2 cost point	Efficiency, η	Capital cost (M$)	CO_2	Citation
Steam reforming	8	9	3	9	6
Dry reforming	7	6	3	9	1
Steam reforming-plasma torch	8	10	3	9	0
Partial Oxidation oil	9	8	2	3	0
Bio photolysis	8	1	0	10	1
Dark Fermentation	8	8	9	10	2
Photo Fermentation	7	1	8	10	1
Gasification of biomass	8	4	8	5	1
Pyrolysis	8	5	4	1	8
Photo biological (photoelectrochemical)	1	1	8	0	3
Electrolysis	1	8	8	0	10
Thermolysis	2	4	7	0	1
Hybrid thermochemical cycles	4	5	9	0	0
Coal gasification	6	5	1	3	1
Hydrogen production from natural gas reforming	6	6	3	2	1

Table 3. Distribution of processes by efficiency from the sources.

Type of the process	Efficiency of the process
Direct use of water for generating of hydrogen, electrolyzes	~55 %
Use of natural gas for generating of hydrogen	~78 %
Use of RES – PV and wind generators for hydrogen generation	~31 %
Use of chemical elements for hydrogen generation, as well as other energy sources emission producers in the atmosphere, like biomass resources	~48 %
Usage of energy sources producing CO_2 while producing hydrogen, like the coals	~65%

5 Electrolyzers

Electrolysis is a chemical process. With it, by means of an electric current, the water molecule is split into hydrogen and oxygen:

$$H_2O + \text{electricity} + Q \dashrightarrow \tfrac{1}{2}\, O_2 + H_2 \tag{1}$$

Oxygen is released at the anode and hydrogen at the cathode. The movement of electrons is in the direction from the anode to the cathode. There are different types of electrolyzers according to the type of cathode and electrode material used, the presence of a membrane, solution, and others. For example, when the anode and cathode are in direct contact with the coil, the formation of a layer preventing the hydrolysis process is not allowed. Effectiveness is over 95% [29, 30 - 35]. Regarding the membrane, they can be alkaline, oxide solid type, or proton electrolyzing type membrane [24].

Proton membrane electrolyzers are the so-called (PEM) type. With higher capital investments, both quality and efficiency are higher. The material from which they are manufactured plays a significant role in simultaneously increasing the efficiency and cost of investing in expensive metals such as platinum, ruthenium, iridium, or others. Gas losses depend on the construction of the housing and the protective layer applied to the walls of the electrolyzer. Their advantage is the production of pure hydrogen purity up to 99.999% [24].

Alkaline Water Electrolyzers (AWE). AWE Consequently, the purity of the produced hydrogen is 99.5 to 99.9% and can be increased up to 99.999% by catalytic gas purification processes [24]. The electrolyte is important. It can be 20–40% sodium hydroxide (NaOH) or potassium hydroxide (KOH). Anodes are Ni. Productivity is affected by the concentration of the corrosive solution. Compared to other types of electrolyzers, these consume the most energy and have the lowest process efficiency.

Alkaline combined electrolyzers. Alkaline anion exchange membrane (AEM) – These are made to eliminate the disadvantages of the two previous types. The solution is again a base with a lower concentration, but the anodes can be made of nickel alloy (the cathodes of Ni-Fe, and NiFe2O4), the membranes – Mg-Al LDH. These types are the so-called Alkaline anion exchange membrane (AEM).

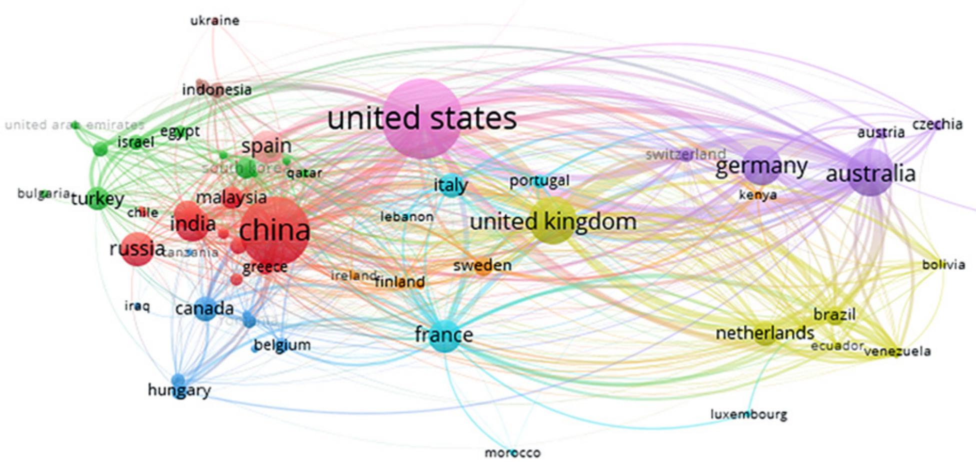

Fig. 3. Notoriety through citations on the topic of Hydrogen pyrolysis.

Solid oxide electrolyzer (SOE). Electrolyzers with lanthanum strontium manganite, zirconium on the cathode, and ceramic on the anode are the SOE type. They are high temperatures, unlike the previous three types. Energy consumption and efficiency are high. This is one of the most unattractive methods due to the high cost of installation and the need for a power supply.

It is possible to use renewable sources for power supply, considering what the consumption, power mode, maintenance, and efficiency will be. The green type of hydrogen production is targeted for the future. That is why the possibility of supplying the electrolyzers with energy from RES sources is important. The efficiency of electrolyzers is not unimportant, with productivity to cost per unit produced being one of the main indicators. Water electrolysis is not one of the most efficient in terms of capital investment in the production of green hydrogen [24, 28, 30]. Figure 3 shows the parameters of criterion citations. Table 4 presents a point system for comparing electrolysis methods.

Table 4. Point system for kind of electrolyzers.

Criterion	**PEM**	**AWE**	**AEM**	**SOE**
Fame	3	3	3	1
Efficiency	6-7	6-7		9
Energy need	6	6	6	1
Density of the current	6	4	2	3
Continuation	5	5		2
Lifetime	4	9	1	4
Currency consumption	4	4	4	2
Expected costs	3	4	6	8
Cost	3	4	8	8
Hydrogen cost	1	1	1	1
CO_2-eq/kg H_2	0	0	0	0
Citation	5	1	10	2

6 RES to generate hydrogen used in hydrolysis

The main RES are photovoltaics, wind generators, and combined plants. The generation of electric current on the anode and cathode is used for the hydrolysis process.

Solar panels energy, used for hydrogen production, where the main disadvantages of the method are: the lack of sunlight at night, the low efficiency of the method of up to 31%, and the high investment costs [12, 25].

Wind generators. Another RES method for generating hydrogen production capabilities. Wind turbines produce alternating current (AC) that varies in magnitude and frequency as the wind speed changes. The energy from the wind turbine is converted from AC form to direct current (DC) and after that is used by the electrolyzer for the production of hydrogen from water or through another chemical element [1], [2].

Here, too, the main drawback is the generation of energy in the cases of movement of air masses, and the process is expensive and inefficient.

Possible systems using RES to generate energy for hydrogen

Technical-economic evaluation and comparison of technologies is possible through the parameters of the levelized cost of electricity LCOE \$/kWh. and The Levelized cost of hydrogen, LCOH \$/kgH_2 [3]. In this method, all operating and capital costs are used to estimate the hydrogen production process. The results are about invested euros per kg of the produced product, but the data for transport and storage of the production are not taken into account. This method can be used to compare the production of hydrogen in different color ranges.

Solar radiation is used to produce electricity by collecting and concentrating it using a solar collector (eg flat plate collector (FPC) and parabolic trough collector (PDC)) [4]. Production varies by latitude, season, day length, dustiness, and other environmental factors [5].

The electricity of wind turbines varies throughout their operating period. The cost of electricity from offshore platforms is lower than that from onshore generators.

There are also combined systems for producing electricity with solar panels and wind turbines.

The main parameters for comparison are the amount of electricity and LCOH and LCOE. For the point system, average values were taken from published studies. For different regions of Bulgaria, they will have different values, but the points will be approximately the same, due to the same relative influence.

Table 5. Point system for kind of source.

Kind	lCOH	LCOE - point
Coal, black	2	2
Natural gas grey	3	2
Nuclear	4	3
Geothermal	3	3
Biomass	5	4
Solar csp	10	8
Solar pv	10	6
Wind offshore	8	8
Onshore wind	7	6
Solar and Wind	5	6

The LCOH of hydrogen production ranges from 0.054 $/kWhH$_2$ (1.78 $/kgH$_2$) to 0.103 $/kWhH$_2$ (3.4 $/kgH$_2$) in the city of Corum in Turkey, which is the region with relatively This shows that while uses 100% power from the grid, PV-based LCOH is an advantage because it is particularly sensitive to electricity costs, LCOH in PV-alkaline system is lower than in PV-PEM system, hydrogen production by trigeneration, powered from natural gas, which produces low carbon emissions, appears to be a good alternative production method with low LCOH gas prices, the trigeneration system or its combinations may have a higher LCOH than PV hydrogen [1], [5], [6]. The table 5 is based on data from [7], [8], [9], [10]. By adjusting the PV panels or the angle of the wind turbine blades, better parameters may be obtained, which is subject to further research. At the same time, tolerances for mechanical strength must be observed to avoid limited stress within the specified limits [37, 38].

Hydrogen can be produced in many ways, not only through chemical methods. Almost any type of energy carrier may be the basis for generating the element hydrogen. From the shown in the article research, can be seen that, at applying the "ranking" evaluation, the water is defined as a raw material for hydrogen electrolysis, as one of the promising and effective ones.

7 Conclusion

To reduce the carbon footprint, achieve increased efficiency, and meet the criteria for sustainable development, it is possible to use hydrogen in natural gas systems. The available regulatory framework, financial interest, and solutions from the major companies have been established. Despite some inconveniences in the application of hydrogen such as increased diffusion and slightly reduced calorific value, there is indisputable evidence of its effectiveness and a major role in reducing the carbon footprint. Given the development of technology, the need to increase the amount of hydrogen is increasing. Therefore, it is necessary to find sufficiently effective sources that can be compared.

To achieve the objective in the paper, hydrogen sources were considered as sources of carbon emissions. Then the hydrogen production methods are classified and evaluated. For this purpose, a point system and criteria such as price per kg of hydrogen, quantity of carbon emissions, efficiency, maturity of the technology, and price of carbon emissions were chosen.

From the proposed point system, it can be concluded that electrolysis is a promising option for carbon-free hydrogen production from renewable and nuclear resources. It is a process of using electricity to split water into hydrogen and oxygen in an electrolyzer. The completeness of the study includes the development of a point system for evaluating the main types of electrolyzers, as well as the type of renewable energy. A final and accurate assessment cannot be given because the impact of renewable energy sources depends on the mix of the specific country.

It is recommended that the energy source is renewable energy and the alternatives are compared based on the LCOH and LCOE parameters.

The comments and conclusions are not final and definitive, because they can be enriched and developed as the number of applications, infrastructure development, and innovation increases.

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