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SWOT ANALYSIS OF HYDROGEN ECONOMY

EKONOMIJA VODIKA S SWOT-ANALIZO

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Abstract

The paper deals with the types of hydrogen production, methods for its storage and transport, and possibilities of the end use of hydrogen. The basics of the hydrogen economy are described briefly, and then the SWOT analysis is performed of the hydrogen economy. The strengths, weaknesses, opportunities, and threats of the hydrogen economy are summarized in the SWOT analysis. The biggest problems and threats, with the possibilities of solving those problems, are summarized based on that analysis. The SWOT analysis considers aspects of the hydrogen economy e.g. energy demands, financial difficulty, safety, and awareness about hydrogen. The Conclusions involve suggestions on how to avoid the above-mentioned awareness, and how to increase hydrogen utilization.

Povzetek

Prispevek obravnava vrste pridobivanja vodika, načine njegovega skladiščenja in transporta ter možnosti končne uporabe vodika. Na kratko so opisane osnove ekonomije vodika, nato pa je opravljena SWOT-analiza ekonomije vodika. Prednosti, slabosti, priložnosti in nevarnosti vodikovega gospodarstva so povzete v SWOT-analizi. Na podlagi te analize so povzeti največji

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problemi in nevarnosti z možnostmi reševanja teh problemov. SWOT-analiza upošteva vidike vodikovega gospodarstva, npr. energetske zahteve, finančne težave, varnost in ozaveščenost o vodiku. Sklepi vključujejo predloge, kako se izogniti zgoraj omenjenemu zavedanju in kako povečati izkoristek vodika.

1 INTRODUCTION

Nowadays, industrially developed countries are using energy mainly from fossil fuels, which are not infinite resources. That is causing faster development in energy resources and possibilities of accumulation energy. The main alternative sources are renewable energy resources with low negative impact on the environment. Renewable resources are difficult to predict in terms of production. This causes the necessity to accumulate energy during high energy production. Current ways for energy accumulation are, e.g., pumped-storage hydroelectricity or batteries. Hydrogen represents another way to accumulate energy. The hydrogen economy deals with issues around the accumulation of energy in hydrogen form, e.g. from renewable sources or fossil fuels. There is an effort to find the best ways for the production, storage, transport, and end use of hydrogen.

2 HYDROGEN PRODUCTION

Production of hydrogen is a process where there is a splitting chemical bond of water which produces separated hydrogen and oxygen. We divide the hydrogen in the color spectrum. Every color depends on the method of production, see Table 1. Each color corresponds to a different extraction process. Nevertheless, the steam reforming of fossil fuels creates the most greenhouse gases. It is the most used method of hydrogen production. Selected methods of hydrogen production are described in Table 2.

***Table 1:** Color marking of hydrogen*

Color	Method of production
Gray hydrogen	Hydrogen is produced by the steam reforming of fossil fuels. Nowadays, it is the most used method of hydrogen production. This method doesn't use capture devices.
Brown/Black hydrogen	The process of hydrogen production is using black or brown coal. It has the worst impact on the environment.
Blue hydrogen	Hydrogen is produced by the steam reforming of fossil fuels with capture devices. The reduction of greenhouse gases is around 90 %.
Pink hydrogen	Hydrogen is produced through electrolysis, using a high temperature from nuclear reactors. It can also be referred to as red or purple hydrogen.
Turquoise hydrogen	A process called methane pyrolysis is used. In the future, it may be valued as a low-emission hydrogen. It depends if the process is powered by renewable sources.
Yellow hydrogen	It is a new phase. The electrolysis uses solar energy.
White hydrogen	Geological hydrogen is found in underground deposits and created by fracking. There is no strategy for how to use this hydrogen.
Green hydrogen	The energy for electrolysis comes from renewable sources like photovoltaic panels or wind turbines.

Table 2: *Hydrogen production method*

Method of production	**Brief description of production**
Electrolysis	The chemical bond of water is split by an electric current.
Thermochemical cycles	An endothermic process where energy from nuclear or solar sources is used for the thermal splitting of water.
Steam reforming of natural gas	The endothermic reaction of natural gas and water vapor. Water vapor has a temperature around 750 – 900 °C. This process creates hydrogen, carbon monoxide, and a smaller amount of carbon dioxide.

Nowadays, mainly fossil fuels are used for hydrogen production, which amount is around 96% of the total production. Electrolysis of water covers the rest, just 4%, see Figure 1.

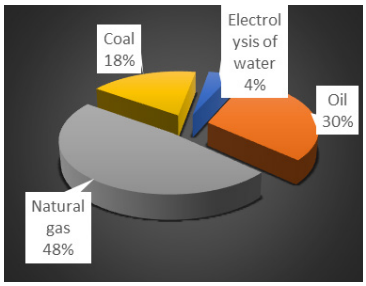

Figure 1: *Division of hydrogen production*

3 HYDROGEN STORAGE

Hydrogen can be stored in different forms, and every form has specific energy demands. Options for storage are hydrogen in gas form, liquid hydrogen and hydrids, where the hydrogen is bound to different alloys.

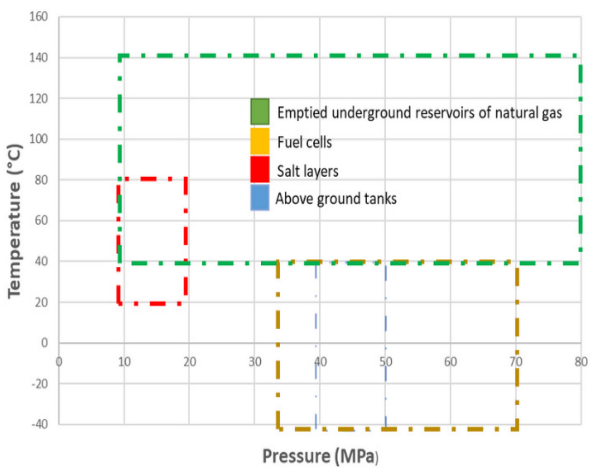

Figure 2: *Division of hydrogen production*

3.1 Storage of hydrogen in gas form

For industry and large-capacity hydrogen storage, it is convenient to store hydrogen in a gas form. In gas form hydrogen can be stored in pressure vessels above the ground or undersea. For large-capacity hydrogen storage emptied underground reservoirs of natural gas or salt layers are the most advantageous. Every method for hydrogen storage requires different temperatures and pressures, see Figure 2. In this method of storage, energy losses are caused by compression devices for compressing hydrogen, or, in the case of underground reservoirs, some of the hydrogen settles in the micropores of the soil.

3.2 Storage of hydrogen in liquid form

In the development of storage hydrogen in liquid form the NASA organization has a major share, where liquid hydrogen is used as rocket fuel. Liquefaction is an energy demanding process where the hydrogen must be cooled at a temperature around -253 °C. This process consumes 15,1 MJ/kg energy *[1]*. The energy needs for hydrogen storage in a liquid form are affected by gas purity, because it is necessary to separate other gases (expected helium) from the hydrogen. Mainly oxygen separation is very important, because the concentration of more than 1 mg of oxygen on 1 kg of hydrogen causes an explosion *[1]*. Other energy losses are caused by the transition of hydrogen from orthoform to paraform. Orthoform has symmetric spins of atoms, and in the paraform, these spins are not symmetric. Para-hydrogen is more stable at lower temperatures, and has a lower enthalpy capacity. Therefore, when hydrogen is passing from orthoform to paraform, the heat is released, which increases the energy requirement.

3.3 Storage of hydrogen in a hydrid form

Storage reservoirs in the case of the hydrid form are smaller than other forms. This type of storage is suitable for end consumers. Hydrogen is bound to other energy carriers, like metal and metal alloys, which creates metal hydrids. For every metal alloy it is required to find the right temperature and pressure when the hydrogen is bound to the metal. It is an exothermic reaction, where, during the fulfilment of the reservoir heat is released and it is necessary for the reservoir to cool down, because this can cause the release of hydrogen. To release hydrogen from the reservoir, the reservoir must be heated or depressurized.

4 HYDROGEN TRANSPORT

Hydrogen can be transported in gaseous, as well as liquid form. For longer distances hydrogen can be distributed through long-distance gas pipelines, which are developed in every economically advanced country. For transport over shorter and medium distances, up to approximately 500 km, it is economically advantageous to transport the hydrogen in liquid or hydrid form.

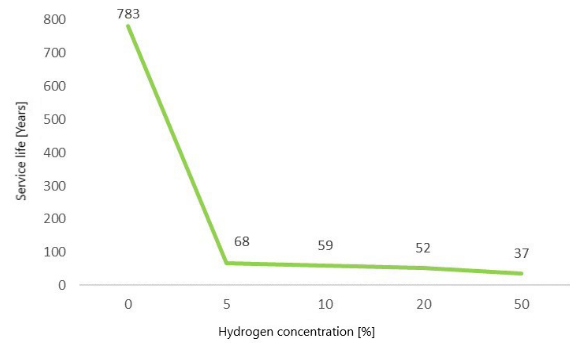

***Figure 3:** Effect of bigger hydrogen concentration on the service life of the currently used pipelines*

4.1 Transport of hydrogen in gas form

To transfer the same amount of energy it is necessary to transport a three times bigger amount of hydrogen compared to natural gas, because hydrogen has a smaller heat value *[1]*. Hydrogen has a nine times smaller density than natural gas, so we can transport more hydrogen. The problem occurs at pressures higher than 5.6 MPa, when the heat value of natural gas increases and hydrogen cannot compete with natural gas. *[1]* Choosing the right gas flow, a turbulent flow, we can ensure the transport of up to 280% of the volume of hydrogen compared to natural gas, which represents approximately 95% of the energy equivalent. *[1]* The next problem of hydrogen transport in gas form is hydrogen embrittlement, where particles of the hydrogen penetrate to the material structure and cause hydrogen embrittlement. The larger amounts of pressures and concentration of hydrogen cause faster hydrogen embrittlement. It is an undesirable phenomenon which causes bigger financial investments. In Figure 3, we can see how the hydrogen concentration affects the service life of steel material. *[7]*

4.2 Transport of hydrogen in liquid form

Despite energy losses, hydrogen transport in liquid form is preferable, mainly over short distances, see Figure 4.

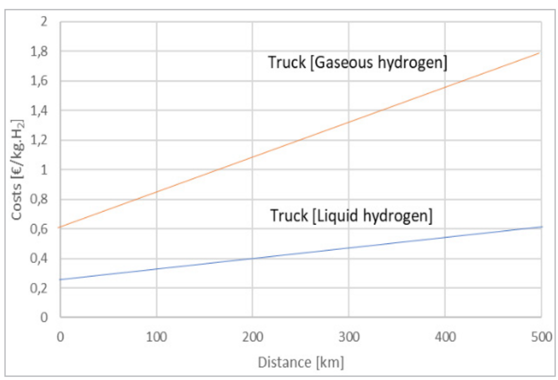

***Figure 4:** Financial costs of transport for shorter distances*

Economically, costs for gaseous transport are affected by the demand for 3 times more hydrogen than natural gas. For comparison, the financial costs of different ways of hydrogen transport are shown in Table 3.

Table 3: *The comparison size of hydrogen containers. The calculated volume is needed for the storage amount of energy of 1 kWh.*

Method of storage	Density [kg/m²]	Energetic density [MJ/m³]	Energetic density [kWh/m³]	Volume [m³]	Volume [l]
Gaseous hydrogen	0.09	10	2.78	0.36	359.712
Gaseous hydrogen under a pressure of 30 MPa	22.5	2 700	750	0.0013	1.33
Liquid hydrogen	71.9	8 700	2 416.67	0.000414	0.41
Natural gas	0.668	37.4	10.39	0.096	96.25
Methanol	0.79	17 000	4 722.22	0.000212	0.21

5 USES OF HYDROGEN

The use of hydrogen in power engineering and as fuel should help the transition to a less environmentally harmful way of producing electricity, heat, or fuel. Hydrogen is deemed to be a prospective secondary energy source. Its application is universal – e.g. power engineering (electricity and heat production), transport, metallurgy, synthetic fertilizer production, usage in the oil industry.

5.1 Uses in power engineering

Hydrogen can help in the decarbonization of electricity production. Green hydrogen can potentially store 4 – 20% of energy from renewable sources. These percentages can increase with an increasing number of renewable sources. *[4]*

We can use hydrogen in thermomechanical cycles via the Carnot turbine, because, when hydrogen is burned with oxygen, it does not produce CO_2. If we burn hydrogen with air, it will have 1.88 mol of nitrogen that decreases part of the thermal energy *[1]*. During the burning of hydrogen with air, we do not achieve the same combustion temperature as in combustion with oxygen, so the whole process of accumulation of energy has lower efficiency.

Hydrogen has a higher flame temperature (2400 K) than natural gas, so it can be good for heat production *[1].* Also, lower energy is required for lighting the flame. Higher temperatures need appropriate technologies that can resist heat. Because 3 times more hydrogen than natural gas is needed to transfer the same amount of energy, hydrogen is currently only blended into gas pipelines. However, it is an opportunity to decarbonize the heating industry in the future.

One of the remarkable methods for large-scale hydrogen production is a thermochemical water decomposition using heat energy from nuclear, solar, and other sources. Water splitting thermochemical cycles replace the thermal decomposition of water with several partial reactions, and they represent an environmentally attractive way for hydrogen production without using fossil fuels. Hydrogen produced via the mentioned cycles could be used for electricity and heat production, as well as a fuel.

5.2 Uses in fuel cells

Fuel cells are electrochemical systems in which the chemical energy of the fuel is converted to electrical energy through the oxidation process. Losses in this system are caused by low-potential heat. The efficiency of this system depends on the activation overvoltage of the electrodes, ohmic and concentration overvoltage.

Fuel cells have better efficiency up to a temperature of 800 °C *[8]*. With increasing temperature the equilibrium oxygen-hydrogen tension decreases, and, from a thermodynamic point of view, the efficiency also decreases. There are several types of fuel cells, which differ in functional principle and suitability for use. Nowadays, fuel cells do not represent an adequate large-capacity source. Fuel cells are applied in a direct current source for electric motors in cars. Fuel cells are used mainly in the automotive and aerospace industries. Fuel cells are, for example, a source of energy for space shuttles, and they were also used in the Apollo program. They are also used in submarines. Currently, some automobile manufacturers produce cars that run on hydrogen, and there are also buses which use hydrogen as a fuel. With the expansion of this type of cars, the network of hydrogen filling stations is expanding, for example, in Slovakia, the first hydrogen filling station was put into operation in 2022. Most hydrogen stations are in Japan (almost 150) and Germany (almost 100).

6 SWOT ANALYSIS

SWOT analysis is a comprehensive assessment of internal and external factors. Th strengths of SWOT analysis are simplicity, clarity, and complexity. In the internal analysis we compare S (strengths) and W (weaknesses). Parts of the external analysis are O (opportunities) and T (threats).

***Table 4:** Criteria of SWOT analysis*

	S – Strengths		W – Weaknesses		O – Opportunities		T – Threats
S1	Accumulation method that doesn't have a negative impact on the environment – depends on the production method	W1	Hydrogen, due to its properties and high diffusion, causes hydrogen embrittlement of the material	O1	Creation of new job opportunities – it is a new technology that requires new, professionally educated people	T1	New technology – the possibility of higher danger
S2	Use of renewable sources in production – electrolysis of water, thermochemical cycles	W2	Requiring a 3 times more amount of hydrogen to transfer the same amount of energy as natural gas, due to lower calorific value	O2	Energy independence – reduced dependence on imports	T2	High investment, need for staff training, developing new technologies etc.
S3	Slowdown in the decline of the Earth's fossil fuel reserves (oil, natural gas)	W3	High financial costs of hydrogen production	O3	Reduction of environmental pollution – depending on the production method (green hydrogen)	T3	Currently underdeveloped infrastructure

S4	A new energy carrier – less dependence on fossil fuels	W4	Energetic intensity of storage – liquefaction, gas compression	O4	Opportunity to use old depleted underground natural gas reservoirs	T4	Competition from cheaper energy sources (fossil fuels)
S5	Building new refuelling stations for a hydrogen economy	W5	Low efficiency of fuel cells, need to provide new technology to increase efficiency	O5	Reducing commodity price fluctuations	T5	Lack of information delivered to the public

The result of the contribution is a SWOT analysis of the hydrogen economy. The criteria used in the SWOT analysis are shown in Table 4. In Table 5 there is a comparison matrix, from which we get specific results about strengths, weaknesses, opportunities, and threats. In Table 5, scoring is used on a scale of minus 5 to plus 5, where minus 5 represents the worst negative mutual influence and 5 represents the best positive mutual influence.

Table 5: *Comparison matrix*

		Internal factors												
		S – Strengths						W - Weaknesses						
Key external factors	O - Opportunities T – Threats	S1	S2	S3	S4	S5	The sum of the ratings O,T/S	W1	W2	W3	W4	W5	The sum of the ratings O,T/W	Final evaluation
	O1	0	5	3	5	5	18	4	2	-2	3	3	10	28
	O2	2	5	3	5	3	18	2	3	3	5	4	17	35
	O3	5	5	3	3	3	19	3	2	4	3	3	15	34
	O4	3	0	-4	2	1	2	1	4	3	1	0	9	11
	O5	1	3	2	5	1	12	3	1	5	4	4	17	29
	T1	0	-2	-4	-4	-2	-12	-5	-3	0	-4	0	-12	-24
	T2	-1	-2	-4	-5	-3	-15	-3	-2	-5	-3	-5	-18	-33
	T3	0	-1	-2	-3	-5	-11	-1	-3	-5	0	-3	-12	-23
	T4	-5	-5	-5	-5	-5	-25	-4	-5	-4	-4	-3	-20	-45
	T5	-5	0	-2	-2	-1	-10	-3	2	-3	0	-3	-7	-17
The sum of the ratings S,W		0	8	-10	1	-3	-4	-3	1	-4	5	0	-1	-5
Scale S / W		35	25	15	15	10	/	15	25	20	30	10		

7 CONCLUSIONS

From the SWOT analysis we found out that the most prominent strength is S2 – Using renewable sources, immediately followed by S1 – the Accumulation method without a negative impact on the environment. In the strategy we should focus on these strengths, and ensure that T4 and T5 will be reduced. T4 – Competition from cheaper energy sources, can be countered by increasing renewable sources that will be used for hydrogen production, or possibly thermochemical cycles. T5 – Lack of information delivered to the public, can be countered by lectures, various discussions, articles, and general propagation. The biggest weaknesses are W2 – Requiring a bigger amount of hydrogen than natural gas, and W4 – The energetic intensity of storage. W2 is related to the opportunity of O4 – the Opportunity to use old depleted natural gas reservoirs. These depleted natural gas reservoirs are good for high-capacity storage. Storage of hydrogen is an energetic challenge, because there are big energy losses. When hydrogen is compressed to 350 bars, approximately 15 – 20% of the energy contained in the fuel is required for the function of compressors, measuring devices, etc. Hydrogen in liquid form has bigger losses, approximately 30 – 40% of energy contained in the fuel is needed for liquefaction. Despite the higher energy intensity of storage, some opportunities have positive impacts, like O2 – Energy independence, and O5 - Reducing commodity price fluctuations.

Acknowledgements

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