THE HYDROGEN ROLE IN THE TRANSITION TOWARDS 100% ENERGY FROM RENEWABLE SOURCES

ROLUL HIDROGENULUI ÎN TRANZIȚIA CĂTRE 100% ENERGIE DIN SURSE REGENERABILE

Dumitru BRAGA[1]

Abstract: *The last few decades are marked by an upward trend of interest in the use of hydrogen for energy purposes. This interest is due to the belief that hydrogen can contribute to the energy transition towards 100% renewable energy sources. The combination between renewable energy sources and green hydrogen can accelerate fossil fuel replacement and climate change mitigation. The use of green hydrogen can eliminate the disadvantages of renewable energy resources compared to fossil energy sources. Besides this, hydrogen can be used for national energy security, long and short-term energy storage, energy quality ensuring, synthetic fuel production, etc.*

Keywords: energy transition, hydrogen, renewable energy sources, synthetic fuels, energy storage, fuel cells.

Rezumat: *Ultimele decenii sunt marcate de un trend ascendent a interesului pentru utilizarea hidrogenului în scopuri energetice. Acesta se datorează încrederii că hidrogenul poate contribui la tranziția energetică către 100% energie din surse regenerabile. Tandemul dintre sursele regenerabile de energie și hidrogenul verde poate accelera substituirea combustibililor fosili și atenuarea schimbărilor climatice. Utilizarea hidrogenului verde poate atenua dezavantajele resurselor regenerabile de energie comparativ cu sursele de energie fosilă. Acesta poate fi utilizat pentru asigurarea securității energetice naționale, stocarea energiei pe termen lung și scurt, calității energiei, producerea de combustibili sintetici etc.*

Cuvinte cheie: tranziție energetică, hidrogen, surse regenerabile de energie, combustibili sintetici, stocare energiei, celulele cu combustie.

[1] Ph.D. Eng., University Lecturer, Department of Energetics, Technical University of Moldova, e-mail: dumitru.braga@tme.utm.md

1. Introduction

Fossil fuels have numerous advantages compared to renewable energy sources: can be easily converted into other forms of energy by a simple combustion process, stored in huge quantities, used at the necessary time and place, etc. However, the fossil fuel combustion process is the main source of greenhouse gases emissions which lead to the acceleration of the climate change phenomenon. On the other hand, the reserves of natural gas, petroleum, and coal are finite [1,2] and can be depleted in 35, 37, and, respectively, 107 years [3].

Another challenge is to manage and cover safely and sustainably the continuously growing energy demand. Widely known is that renewable energy sources can relatively easily substitute entire or at least a considerable part of energy obtained by the fossil fuel combustion process. The main issues of renewable energy source use include unpredictable character (e.g. solar and wind energy), limited possibilities of storing in enough quantities, time shift between peaks of energy demand and availability of these sources, limited installed capacities, and high territorial dispersion of these [4,5].

The combination of renewable energy sources systems and hydrogen systems represents a real solution for these challenges. Hydrogen has been produced and used in industry for a long time. But, with the aggravation of the energy crisis, green hydrogen, produced by water electrolysis using renewable energy sources, attracts more attention as a new pure energy source and an efficient method of energy storage [6]. The use of green hydrogen as energy storage or energy source could have a huge potential for large scale integration of renewable energy sources [4,5], decarbonation of the economy [7], and energy security [8,9]. According to IRENA's Roadmap, it is expected that hydrogen will cover about 6% of the world's energy balance by 2050, and according to the Hydrogen Council about 18% [9]. Today, global hydrogen demand is 8 EJ, which is expected to increase to 29 EJ by 2050.

About 120 million tons of hydrogen are produced worldwide each year, which is 1/3 of the total production of pure gas. About 95% of hydrogen is produced in the industrial processes of thermochemical treatment of coal and natural gas, and only 5% in the processes of water electrolysis (chlorine production). Hydrogen production is responsible for 830 million tons of CO_2 equivalent per year at the global level [9]. Therefore, to truly benefit from the use of hydrogen, it must be produced from renewable energy resources.

The promising and sustainable method of hydrogen production, with zero emissions, is the water electrolysis that can be powered by renewable energy resources like photovoltaics or wind systems (green hydrogen). But, green hydrogen has an insignificant share [9]. Barriers to increasing the share of green hydrogen include [10]:

- high costs for obtaining green hydrogen (double or even triple compared to gray hydrogen), as well as for technologies that use hydrogen fuel cells or by direct combustion (e.g. hydrogen-based vehicles cost 1.5 ÷ 2 times higher compared to fossil fuels) or for synthetic fuels derived from hydrogen (e.g. aircraft fuel is more than eight times more expensive than fossil fuels);
- the lack of infrastructure requires the production of hydrogen near its use sites. Globally, hydrogen transport and use infrastructure includes only about 5,000 km of hydrogen pipelines (compared to 3 million km of natural gas pipelines) and 470 hydrogen refueling stations compared to 200,000 diesel and gasoline refueling stations from USA and EU);
- high energy losses: green hydrogen production (30 ÷ 35%); hydrogen conversion in other chemicals (e.g. ammonia 13 ÷ 25%); hydrogen conversion into electricity (40 ÷ 50% for fuel cells); hydrogen transport (10 ÷ 12%);
- ignoring the importance of green hydrogen - the absence of world statistics, the lack of targets for its use or tools for its promotion, lack of market for green hydrogen, etc.
- ensuring the sustainability criterion of the green hydrogen production process in the case of electrolysis connected directly to the public electricity grid, or the concomitant connection to the electricity grid and sources based on RES.

It can also promote the large-scale integration of variable and renewable power generation, which can be converted into hydrogen via electrolysis and stored similar to batteries for applications in various industries including mobility [11]. Hydrogen fuel cell vehicles (HFCVs) possess great advantages of fast and convenient refueling and exhibit significant potentials for green, clean and zero-carbon mobility. They have attracted much attention all over the world. Hydrogen energy systems (HESs) are experiencing rapid materialization, especially for HFCV refueling [12].

In [7,13] it is presented the strategy for the energy transition to the net carbon neutrality of the Republic of Moldova. This strategy supports the massive integration of the Variable Renewable Energy Sources (VRES) into the power system, foreseen electrification of the main national economy sectors and the use of hydrogen for energy storage, synthetic fuel production, and supply of the economy with chemicals like methanol or ammonia (fig. 1).

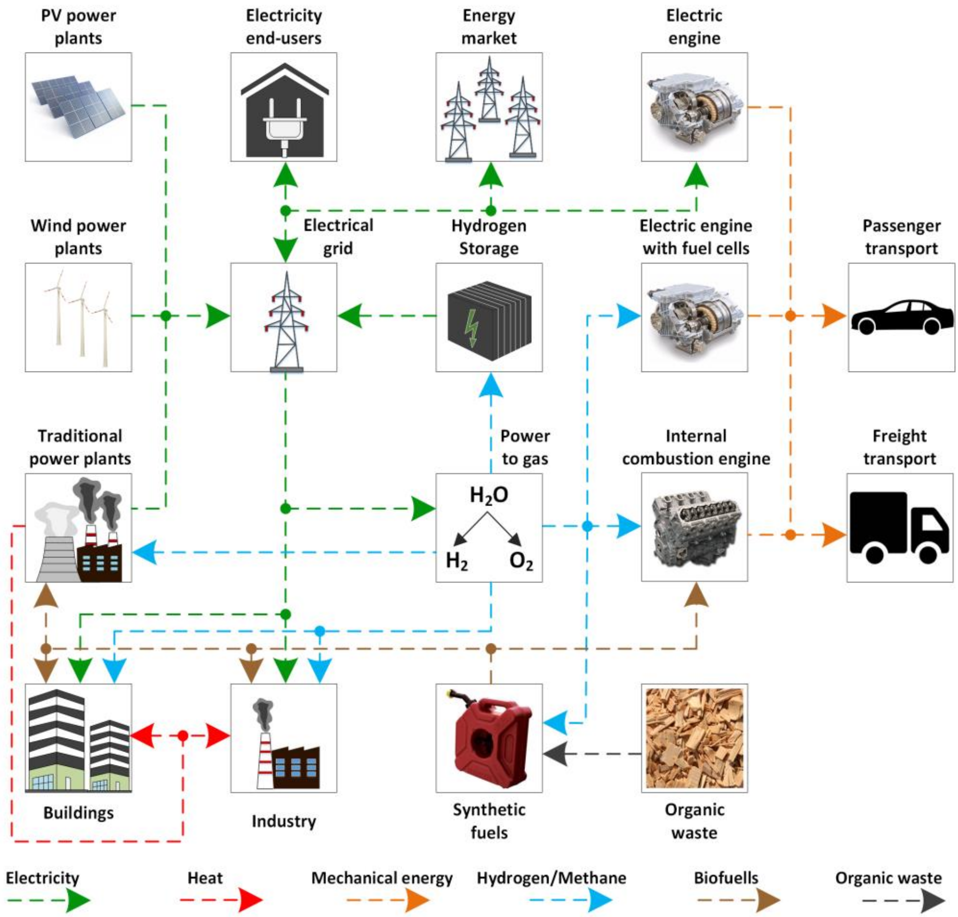

Figure 1. The role of hydrogen in the energy transition [7].

This paper aims to evaluate the importance, opportunity, and feasibility of hydrogen in the integration of renewable energy sources into the Energy System and the decarbonation of the National Economy of the Republic of Moldova based on the concept of decarbonation the national economy.

2. Applied methodology for economic assessment

The main economic indicators which can demonstrate the opportunity and feasibility of hydrogen production and use are total investments (I_t), total discounted costs (*TDC*), and the Levelized cost of hydrogen or derived products ($LCOX$). The choice of the study period T_{sn} depends on the service lifetime of the main systems and equipment. The compared technologies have different service lifetime periods and vary between 10 and 20 years. Thus, the study period is chosen equal to 10 years. The discounted study period $\overleftarrow{T}_{T,i}$ is determined based on the discount rate i:

$$\overleftarrow{T}_{T,i} = [1 - (1 + i)^{-T}]/i. \quad (1)$$

The discount rate is the function of interest rate i_r, inflation rate r_{inf}, and economic risk rate r_{risc}:

$$i = (1 + i_r) \cdot (1 + i_{inf}) \cdot (1 + r_{risc}) - 1. \quad (2)$$

For the period between 2012 and 2020, the average inflation rate in the Republic of Moldova was 5.38%, and the interest rate for energy projects was 2%. The economic risk rate for energy projects is about 1 ÷ 2%.

In the case of technologies with a longer lifetime than the study period, the discounted book value is needed to take into consideration to calculate the Levelized cost of hydrogen:

$$R_{act} = [I_t - (I_t - V_{rez}) \cdot t/T_{sn}] \cdot (1 + i)^{-T}, \quad (3)$$

where I_t represents initial total investment costs, made in the year t; V_{rez} – book value of the capital assets at the end of the study period; t – a year for which is determined the discount residual value (in our case it is the last year of the study period $t = T_{sn}$).

The Levelized cost of hydrogen or other derived products X:

$$LCOX = (TDC - R_{act})/XTA, \quad (4)$$

where TDC represents total discounted costs for hydrogen production, synthetic fuel production, or stored energy; XTA – total discounted production.

Total discounted produced hydrogen, synthetic fuel or stored energy is calculated by multiplying the annual production, or storage X_t and the discounted study period:

$$XTA = X_t \cdot \overleftarrow{T}_{T,i}. \quad (5)$$

Total discounted costs TDC for energy storage systems (ESSs) includes the total investment discounted costs TDC_I, the total O&M discounted costs $TDC_{O\&M}$, and total discounted costs associated with electricity consumption TDC_W, hydrogen compression and storage TDC_{CS}, logistics and distribution TDC_{log}:

$$TDC = TDC_I + TDC_{O\&M} + TDC_W + TDC_{CS} + TDC_{log}. \tag{6}$$

The total investment discounted costs are calculated considering the total required investment cost:

$$TDC_I = \sum_{t=-(d-1)}^{0} I_t \cdot (1+i)^{\theta-1}, \tag{7}$$

where I_t represents investments realized in year t; d – ESSs construction period; θ – the reference year for discounting. Usually, this year $\theta = 0$, the first year before the putting into operation of the ESSs.

Total required investment can be estimated based on the average specific investment cost i_{sp} for the same technologies in a specific region and capacity of the electrolysis, fuel cells, compression, storage, or transport of the hydrogen or derived products C_X:

$$I = i_{sp} \cdot C_X. \tag{8}$$

Other total discounted costs are calculated in the same way considering the respective annual costs and recalculated study period according to the annual rate growth of the respective costs:

1. Total operation and maintenance discounted costs $TDC_{O\&M}$:

$$TDC_{O\&M} = I_t \cdot c_{O\&M} \cdot \overleftarrow{T}_{T,x1}. \tag{9}$$

2. Total discounted costs associated with electricity consumption:

$$TDC_W = X \cdot w_t \cdot \overleftarrow{T}_{T,x2} \cdot LCOE_{VRES}. \tag{10}$$

3. Total discounted costs associated with hydrogen compression and storage:

$$TDC_{CS} = X \cdot c_{sp}^{CS} \cdot \overleftarrow{T}_{T,x3}. \tag{11}$$

4. Total discounted costs associated with logistics and distribution:

$$TDC_{log} = X \cdot c_{sp}^{log} \cdot \overleftarrow{T}_{T,x4}, \tag{12}$$

where $c_{O\&M}$ represents specific O&M costs; c_{sp}^{CS} – specific compresion and storage costs; c_{sp}^{log} – specific logistics and distribution costs; $\overleftarrow{T}_{T,x}$ – recalculated study period function of synthetic rate x; X – production of hidrogen, synthetic fuel or stored energy; $LCOE_{VRES}$ – Levelized cost of energy generated by VRES.

The recalculated study period function of synthetic rate x:

$$\overleftarrow{T}_{T,x} = [1 - (1 + x)^{-T_{sn}}]/x. \quad (13)$$

Synthetic rate x, which considers the costs growth rate r:

$$x = (1 + i)/(1 + r) - 1. \quad (14)$$

3. Hydrogen production

Due to no free hydrogen in nature, it must be obtained from various chemical compounds like hydrocarbons, coal, water, etc. by various processes. To date, no positive energy balance has been obtained between the energy used to produce hydrogen and the energy obtained from its use. In these conditions, nowadays hydrogen is mainly used in the chemical and petrochemical industries, being obtained by thermochemical treatment processes of coal, natural gas, or petroleum products.

Depending on the hydrogen production process, it differs [10]:

- gray hydrogen – produced by coal gasification or catalytic reforming with water vapor of methane;
- blue hydrogen – produced by coal gasification or water vapor catalytic reforming of methane with carbon sequestration resulting in the process of hydrogen production;
- turquoise hydrogen – produced by methane pyrolysis; and
- green hydrogen – produced by water electrolysis process using electricity generated by RES.

The most sustainable way of hydrogen production is the water electrolysis process using the excess electricity generated by VRES. Thus, hydrogen production using electricity generated by VRES leads to the increase of the capacity factor of the power plants using VRES, and as result the reduction of the investment payback period for these types of energy sources. Besides this, the produced hydrogen can be used for electricity generation using fuel cells in the period of peak demands or periods characterized by a lack of wind or sun. So, it contributes to the shaving of the VRES generation curve, energy security and improves the functional characteristics of the power system and energy quality. Green hydrogen can substitute fossil fuels in classic power plants used for internal combustion engines, gas, or steam turbine, improving local and national energy security. Table 1 presents the main physicochemical characteristics of hydrogen.

Table 1. **Physicochemical characteristics of hydrogen**

Characteristics		**Value**
Molecular weight, g/mol		2.016
Liquid phase	Density at 98 kPa [kg/m^3]	71
	Boil temperature at 101.3 kPa [^{0}C]	20.384
	Latent vaporization heat at 101.3 kPa [kJ/kg]	454.26
Gaseous phase	Density at 288 K and 98 kPa, [kg/m^3]	0.082
	Specific heat at 288 K and 101.3 kPa [kJ/(kg·K)]	14.320
	Heat conductivity at 293 K and 101.3 kPa [W/(m·K)]	0.171
	Viscosity at 293 K and 101.3 kPa [kg/(m·s)]	$845 \cdot 10^{-7}$
Limit of flammability in air		4 ÷ 75.6%
Smell		Odorless gas
Aspect		Colorless gas

Table 2. ***Comparison between the flexibility of Alkaline and PEM [14]***

Characteristics	**Electrolysis type**	
	Alkaline	**PEM**
Load range, [% of nominal load]	15 ÷ 100%	0 ÷ 160%
Start-up	1 ÷ 10 minutes	1 second ÷ 5 minutes
The ability to ramp up productivity	0,2 ÷ 20% per second	100% per second
The ability to ramp down productivity	0,2 ÷ 20% per second	100% per second
Shutdown	1 ÷ 10 minutes	Seconds

Water electrolysis is the oxidation-reduction process that takes place at the two electrodes (cathode – a reducer, and anode – an oxidant) when the direct electric current passes through the electrolyte solution or melt. As a result of water electrolysis, electricity is converted into chemical energy of newly formed substances - hydrogen H_2 and oxygen O_2. Figure 2 presents the function principle of water electrolysis and the main types of existing electrolysis. Table 2 presents the comparison between the flexibility of Alkaline and PEM.

Alkaline electrolysis is the most mature technology. Alkaline electrolysis separates water into hydrogen and oxygen using two electrodes placed in solution of water and liquid electrolyte (potassium hydroxide KOH or sodium hydroxide NaOH). The operation parameters of the alkaline electrolysis are the temperature of 40 ÷ 90 ^{0}C, and the pressure of 3.2 MPa. Alkaline electrolysis has an electrical conversion efficiency of about 77% and a slower ability to respond to power supply fluctuation compared to other electrolysis technologies. That is why it is more difficult to use them to flatten the VRES generation graphics [15]. The purity of the obtained hydrogen is over 99.8, and the lifetime is about 60,000 ÷ 90,000 hours [16].

Proton Exchange Membrane (PEM) electrolysis uses ionically conductive solid polymer (e.g. Homogeneous Perfluorosulfonic Acid) to split the water molecule. The operation parameters of the alkaline electrolysis are the temperature of 20 ÷ 80 ^{0}C, and the pressure of 5 MPa. The electrical efficiency of PEM electrolysis can achieve 80%. The dimensions and mass of PEM electrolysis are about 3 times smaller than that of alkaline electrolysis. The PEM electrolysis is more efficient to use in combination with VRES due to its rapid dispatchability and ability to follow the VRES energy output [15]. The purity of the obtained hydrogen is over 99.99, and the lifetime is only 20,000 ÷ 60,000 hours [16]. Thus, PEM electrolysis can be used successfully for VRES power plants or to offer grid services for a power system in the massive presence of VRES sources.

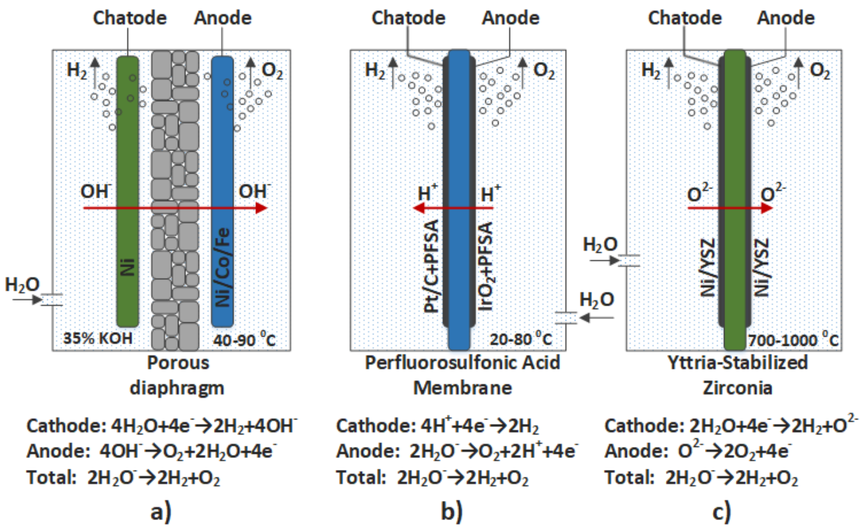

Figure 2. Principle of operation of different types of electrolysis:
a) Alkaline electrolysis; b) Proton Exchange Membrane (PEM) electrolysis;
c) Solid oxide electrolyte (SOE) electrolysis.

Solid Oxide Electrolyte (SOE) electrolysis use ceramic electrolytes (e.g. Yttria Stabilized Zirconia) and is not widely spread commercially. SOE electrolysis has a large range of operation temperature (up to 500 ^{o}C) and can use the waste heat for their operation. The SOE electrolysis has an efficiency of about 74%. This type of electrolysis is suitable to use for example in nuclear power plants, where they can use electricity and heat from the same source. Due to noble metals used for electrodes production, the cost of SOE electrolysis is considerably higher than Alkaline or PEM electrolysis [15]. The purity of the obtained hydrogen is over 99.99, and the lifetime is less than 10,000 hours [16].

The cost of green hydrogen is much higher than that of gray hydrogen due to the higher cost of the energy generated by VRES and the energy intensity of the electrolysis process. Next, it is proposed to evaluate the green hydrogen production costs using Alkaline and PEM electrolysis and VRES in the condition of energy transition of the Republic of Moldova (table 3) [7].

Table 3. **Hydrogen demand for energy transition 100% energy from RES**

Economy sector	**Hydrogen demand [t/year]**		
	Fuel Cell supply	**Natural Gas production**	**Petroleum production**
Residential sector	-	85585	0
Industrial sector	-	21985	1887
Trading and Public Services	-	8813	1897
Agriculture, Forestry and Fishing	-	373	11657
Road Transport	417	-	-
Total	139618		

It is accepted that for the electrolysis process it is used the electricity generated by solar PV and wind power plants. The Levelized cost of energy of the generated electricity is 60 Euro/MWh for solar PV power plants and 40 Euro/MWh for wind power plants [13]. Because of the variability of VRES, it is supposed that the load factor of the electrolysis will be small enough. According to performed simulation [13], the load factor of the electrolysis used in combination with wind power plants is in a range of 10% and 20%, and for that used in combination with solar PV power plants in a range of 30% and 40%. Thus, the load factor of electrolysis is accepted in the range of 10% and 50%. The estimated Levelized cost of hydrogen represents a range between the first case the maximum accepted load factor (50%) and minimum Levelized cost of energy (LCOE) generated by VRES (100% electricity generated by wind power plants) and the minimum accepted load factor (10%) and maximum LCOE generated by VRES (100% electricity generated by solar PV power plants). Accepted specific investment and operation and maintenance costs are presented in table 4. Considering the operation lifetime of the Alkaline and PEM electrolysis, it is accepted study period of 10 years. Service lifetime, specific costs, annual growth rate, Levelized costs of energy generated by VRES are presented in table 10. The results of Levelized cost of hydrogen calculation in dependence of electrolysis technology and source of electricity for electrolysis process are presented in table 5.

Table 4. **Costs associated with hydrogen production and use [13,14,17]**

Parameters		**Alkaline electrolysis**	**PEM electrolysis**	**Alkaline fuel cell**	**PEM fuel cell**	**Hydrogen storage**	**Infrastructure and**
Service lifetime (years) [years]		15	10	15	10	10	-
Efficiency [%]		77	80	63	60		
Specific investments	[Euro/kW]	700	1200	1200	2340	-	-
	[Euro/kWh]	-	-			15	-
Operation and maintenance specific costs	[Euro/(kg $H_2 \cdot h$)]	0.008	0.008	0.008	0.008	-	-
	[Euro/kg H_2]	-	-	-	-	-	7.5
	[Euro/MWh]	-	-	-	-	1.2	
Levelized cost of energy generated by wind / solar PV power plants [Euro/MWh]		40.0 / 60.0					
Discount rate [%]		8.56					
Annual growth rate of O&M costs [%]		2.00					
Annual growth rate of the Levelized cost of energy from VRES, %/year		2.50					
Energy price on Day-Ahead Market [Euro/MWh]	Average	120.3					
	Peak	136.8					
	Off-peak	104.0					
Annual growth rate of the energy price on day-ahead market [%/year]		2.50					

Estimation of Levelized costs of hydrogen (LCOH) shows that for admitted load factor this range is between 2.8 and 5.8 Euro/kg H_2 (71.1 and 172.4 Euro/MWh) for alkaline electrolysis and between 3.4 and 10.3 Euro/kg H_2 (87.5 and 262.4 Euro/MWh) for PEM electrolysis (table 5). If it is considered the load factor for electrolysis (used the excess of generated energy) and the source of energy for this process the Levelized cost of hydrogen range between 4.0 and 5.4 Euro/kg H_2 (101.7 and 137.7 Euro/MWh) for electrolysis using the excess of energy generated by solar PV power plants and between 3.4 and 9.4 Euro/kg H_2 (99.3 and 237.6 Euro/MWh) for electrolysis using the excess of energy generated by wind power plants. Thus, the lowest limit of LCOH for both types of energy sources is at the same level, but the highest limit is considerably higher for electrolysis using energy generated by wind power plants. Evident with using the energy mix from these two types of sources the Levelized cost of hydrogen can be slightly reduced. Next, the obtained Levelized cost of hydrogen is used to assess the energy storage and synthetic fuel costs.

Table 5 - *Levelized costs of hydrogen assessment results*

Parameters			**Value**	
The load factor [%]			10	50
Investments [million Euro]	Alkaline electrolysis		4396.9	879.4
	PEM electrolysis		7537.7	1507.5
	Hydrogen storage		9.4	
Total Investment discounted costs [million Euro]	Alkaline electrolysis		4406.4	888.8
	PEM electrolysis		7547.1	1516.9
Operation and maintenance total discounted costs [million Euro]	Alkaline electrolysis		80.5	16.1
	PEM electrolysis		80.5	16.1
Energy demand for hydrogen production by electrolysis [GWh/year]	Alkaline electrolysis		7148	
	PEM electrolysis		6883	
Total discounted costs associated with electricity consumption [million Euro]	Solar PV power plants	Alkaline	3169.4	
		PEM	3051.7	
	Wind power plants	Alkaline	2112.9	
		PEM	2034.5	
Total discounted costs [million Euro]	Solar PV power plants	Alkaline	7656.3	4074.3
		PEM	10670.0	4575.4
	Wind power plants	Alkaline	6599.9	3017.8
		PEM	9652.7	3558.1
Discounted residual value of the fixed assets [million Euro]	Alkaline system		645.8	128.9
	PEM system		0	0
Levelized cost of hydrogen, [Euro/kg H_2]	Solar PV power plants	Alkaline	6.8	3.8
		PEM	10.3	4.4
	Wind power plants	Alkaline	5.8	2.8
		PEM	9.4	3.4
Levelized cost of hydrogen [Euro/MWh]	Solar PV power plants	Alkaline	172.4	97.0
		PEM	262.4	112.5
	Wind power plants	Alkaline	146.4	71.1
		PEM	237.4	87.5

4. Hydrogen Energy Storage System

The primary function of the energy storage systems is to compensate for the time shift and quantitative differences between the energy generation by VRES and the user's energy load. The increasing presence of VRES in the power system leads to an increase in the variability of available electricity and, respectively, the time shift between electricity generation and demand graphics. The time shift may vary from a few hours to a few days or months. The presence of this time shift leads to the need for frequent shutdowns/starts of conventional power plants covering the basic electricity load and the rapid increase of power generated by them.

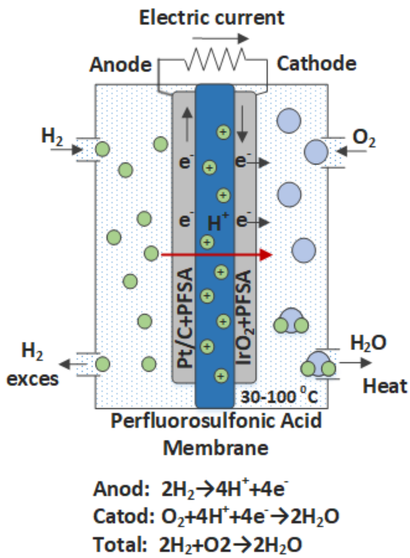

Figure 3. Operation of PEM fuel cell [13]

Electricity storage can be performed at the local level of the energy sources or users, or the central level of the power system. At the local level, ESS is used for flattening sources generation or users' consumption graphics, and at the central level for power system balancing and providing grid services (e.g. ensuring voltage or frequency stability). The hydrogen energy storage systems include a tandem between water electrolysis, that use excess of generated electricity for hydrogen production, and fuel cells used for electricity generation in hours with deficit of energy generation. Thus, the hydrogen energy storage system is based on the conversion of electricity – gas – electricity. There is a wide variety of hydrogen fuel cells: alkaline fuel cell; proton exchange membrane fuel cell; zinc-air fuel cell; protonic ceramic fuel cell etc. The operation of PEM fuel sell is presented in figure 3.

The alkaline fuel cell is the oldest and most widespread technology. It uses as the electrolyte solution of potassium hydroxide and various metals (non-precious) as catalysts at the anode and cathode. The low-temperature alkaline fuel cells operate at temperatures of 23÷70 ^{0}C, and those of high temperatures of 100÷250 ^{0}C. Their average efficiency is about 60%. The disadvantage of this type of cell is the high danger of carbon dioxide contamination. Even a small amount of carbon dioxide in the air leads to the need to purify both oxygen and hydrogen, which involves additional costs. It also reduces the service life of the fuel cell. To overcome this challenge, the oxygen obtained in the electrolysis process can be used as an oxidant.

Table 6. **Levelized costs of stored energy estimation**

Parameters				Value			
HESS load factor [%]				10%	20%	30%	40%
Annual stored energy [GWh/year]				21.9	43.8	65.7	87.6
Investments [th. Euro]	Alkaline fuel cells			3480			
	PEM fuel cells			6786			
	Hydrogen storage system			375			
	Compression system			26.3			
Total investment discounted costs [th. Euro]	Alkaline			3881.3			
	PEM			7187.3			
Total discounted costs associated with hydrogen production [million Euro]	Solar PV power plants	Alkaline	Min.	38.9	77.9	116.9	15.6
			Max.	69.2	138.4	207.7	276.9
		PEM	Min.	47.4	94.9	142.3	189.7
			Max.	110.6	221.2	331.8	442.4
	Wind power plants	Alkaline	Min.	28.5	57.0	85.6	114.1
			Max.	58.8	117.6	176.3	235.1
		PEM	Min.	36.9	73.8	110.7	147.5
			Max.	100.1	200.1	300.2	400.3
Total discounted costs [million Euro]	Solar PV power plants	Alkaline	Min.	45.3	84.2	123.2	162.1
			Max.	75.5	144.7	213.9	283.2
		PEM	Min.	57.0	104.5	151.9	199.3
			Max.	120.2	230.8	341.4	452.1
	Wind power plants	Alkaline	Min.	34.8	63.3	91.9	120.4
			Max.	65.1	123.9	182.7	241.4
		PEM	Min.	46.55	83.4	120.3	157.2
			Max.	109.7	209.7	309.8	409.9
Estimated electricity price on Day-ahead Market (Peak load) [Euro/MWh]				176.18			
The Levelized cost of stored energy [Euro/MWh]	Solar PV power plant	Alkaline	Min.	178.9	166.5	162.3	160.3
			Max.	298.6	286.1	282.0	279.9
		PEM	Min.	225.6	206.5	200.2	197.0
			Max.	475.4	456.4	450.0	446.9
	Wind power plant	Alkaline	Min.	137.7	125.2	121.1	119.0
			Max.	257.4	244.9	240.7	238.7
		PEM	Min.	183.8	164.8	158.5	155.4
			Max.	433.7	414.7	408.3	405.2

Next, it is proposed to evaluate the feasibility of the hydrogen energy storage system for flattening graphics of the energy generation of the solar PV and wind power plants. As the efficiency economic indicator is used Levelized cost of stored energy and compared with Levelized cost of energy on the day-ahead market. As the Levelized cost of energy is taken the average price of electricity on the Romanian day-ahead market, which is projected for the study period. According to performed modeling [13] of functioning of hybrid systems including power plants using VRES and energy storage systems, the load factor of energy storage systems varies in the range of 10 and 15% for wind power plants and 30 and 35% for solar PV power plants in the condition of Republic of Moldova. The initial data (efficiency and specific costs for fuel cells, compressing, and storage systems) are presented in table 4, and the estimated Levelized cost of stored energy in table 6. The hydrogen storage capacity is accepted at 25 MWh and the chosen study period is of 20 years. The low limit of costs corresponds to the lowest Levelized cost of hydrogen, respectively the high limit to the highest Levelized cost of hydrogen.

Compared to the Levelized cost of energy on the day-ahead market, it is observed that the Levelized cost of stored energy is lower in the case of alkaline systems and minimum the Levelized cost of hydrogen. But in all other cases, this cost far exceeds the Levelized cost of energy on the day-ahead market.

5. Synthetic fuel production

Electricity generated by VRES sources can be used to produce synthetic fuels or other products needed by industry, which would partially replace the use of fossil fuels and contribute to power system balancing in the massive presence of VRES, and increasing the capacity factor of sources using VRES. The key element of synthetic fuels production is the production of green hydrogen by electrolysis using electricity from VRES. Hydrogen can be used directly in combustion plants (internal combustion engines) or fuel cells, or it can be converted into other types of gaseous or liquid synthetic fuel (methane, methanol, synthetic natural gas, E-Gasoline, E-Diesel, E-Kerosene), which can be used in the combustion plants of thermal power plants, in industry, in long-distance transport or can be injected into natural gas networks. The characteristics of the different types of fuel are presented in table 7.

Table 7. **Higher and Lower Heat value, and density and density of fuels**

Fuels	**Higher Heat Value [kWh/kg]**	**Lower Heat Value [kWh/kg]**	**Density, $[\text{kg/m}^3]$**
Hydrogen	39.4	33.4	0.090
Methane	15.4	13.9	0.716
Methanol	6.39	5.54	791
Amonia	-	5.17	0.730
Natural gas	14.5	13.1	0.777
Diesel	12.67	11.83	846

The chemical conversion that stands at the base of synthetic fuels production are:

a. Synthetic natural gas (methane) production:

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O, \quad \Delta H^0_{298} = -165 \text{ [kJ/mol]} \tag{15}$$

b. Methanol production:

$$CO_2 + 3H_2 \rightleftharpoons CH_3(OH) + H_2O, \quad \Delta H^0_{298} = -49{,}2 \text{ [kJ/mol]} \tag{16}$$

c. Diesel production:

$$nCO_2 + (3n+1)H_2 \rightleftharpoons C_nH_{2n+2} + 2nH_2O, \quad \Delta H^0_{298} = -125 \text{ [kJ/mol]} \tag{17}$$

d. Ammonia production:

$$0.5 \cdot N_2 + 1.5 \cdot H_2 \rightleftharpoons NH_3, \quad \Delta H^0_{298} = -93 \text{ [kJ/mol]} \tag{18}$$

A source of carbon dioxide is required to produce synthetic fuels like methane, methanol, gasoline, diesel, or kerosene. The integration of carbon dioxide capture systems into synthetic fuel production processes reduces greenhouse gas emissions into the atmosphere. Thermoelectric or thermal power plants using fossil fuels or biomass, industrial processes, waste incineration processes (waste incineration plants), or atmospheric air can be used as sources of carbon dioxide (table 8).

The main challenge for synthetic fuel production is finding a feasible, energy-efficient, and sustainable way to the production of hydrogen. Next, it is proposed to estimate the Levelized cost of fuel (methane, methanol, ammonia, diesel). Table 9 presents synthetic fuel demand for energy transition. The initial data and results of the estimation of the Levelized costs of synthetic fuels are presented in table 10. For fuel production, it is assumed that carbon dioxide is captured from the atmospheric air.

Table 8. **Energy demand for carbon dioxide capture and compression**

Carbon dioxide source	Energy demand [kJ/mol CO_2]	
	Heat	Electricity
Atmospheric air	400	80
Wastewater	242	
Flue gases	163	10
Biogas	90	

Table 9. **Synthetic fuel demand for energy transition**

Sector	Fuel demand [PJ/year]			
	Diesel	Methanol	Ammonia	Natural gas
Residential sector	6.94	-	-	40.08
Industrial sector	0.85	0.60	-	12.08
Trading and Public Services	0.85	-	-	4.84
Agriculture, Forestry and Fishing	5.25	-	0.26	0.20

It is observed that the Levelized cost of synthetic fuels is slightly higher compared to the current price of fossil fuels (imported into the Republic of Moldova), but in the view of continuous increase of the price of fossil fuels on the international market, in not far future synthetic fuel can become a real alternative for sustainable national and global economy (table 10). For example, the cost of synthetic natural gas is $432.1 \div 814.4$ $\mathrm{Euro/th.\,m^3}$ and the price of fossil natural gas is 574 $\mathrm{Euro/th.\,m^3}$ (at the entry into the natural gas transport networks).

6. Electric transport with fuel cells

The transport sector is the second largest user of energy resources, after energy, and, respectively, is an important source of greenhouse gas emissions (about 25%) worldwide. Thus, reducing the use of fossil fuels by electrification this sector is a key element in decarbonizing the national economy.

Electrification of the transport sector can be done in two different ways: direct electrification and indirect electrification. Direct electrification supposes the use of the electric engine and batteries for electricity storage. Indirect electrification supposes the production of hydrogen that is used for synthetic fuel production by hydrogen methanation and its use in traditional vehicles equipped with internal combustion engines or is used to supply electric vehicles equipped with hydrogen fuel cells (FCHEV). Electric motors coupled with fuel cells are also two to three times more efficient than internal combustion engines running on gasoline (considering chain tank-to-wheel). Table 11 presents specific fuel consumption for traditional vehicle and electricity consumption for electric vehicles.

Table 10. **Levelized costs of synthetic fuels**

Parameters			**Synthetic natural gas**	**Methanol**	**Ammonia**	**Petroleum products**
Study period [years]			20			
Annual fuel demand [th. t/year]			1707.8	30.1	13.9	298.4
Efficiency (hydrogen to fuel) [% of HHV]			72	70	67	65
Hydrogen demand [t H_2/t fuel]			0.13	0.25	0.14	0.14
Carbon dioxide demand [t CO_2/t fuel]			1.38	2.75	-	3.14
Carbon dioxide density [kg/Nm^3]			1.98			
Specific investments [Euro/kW fuel]			195	390	400	412
Operation and maintenance specific costs (year 0), [% of total investment]			4			
Total investments [million Euro]			2341.7	34.2	15.9	711.1
Total investment discounted costs [million Euro]			2341.7	34.2	15.9	711.1
Total operation and maintenance discounted costs [million Euro]			1037.4	15.2	7.0	315.0
Minim/maxim Levelized cost of hydrogen [Euro/kg H_2]			2.8 / 6.8			
Total discounted costs associated with hydrogen production [billion Euro]		Min.	5.8	0.2	0.11	1.1
		Max.	14.2	0.5	0.12	2.7
The purity of the obtained CO_2 gas [%]			99			
Energy consumption for CO_2 production and liquefaction [MWh/t]			3.01			
Total discounted costs associated with CO_2 production [million Euro]		Min.	471.8	94.7	-	1073.6
		Max.	707.8	142.1	-	1610.4
Total discounted costs [billion Euro]		Min.	9.7	0.3	0.13	3.2
		Max.	18.3	0.7	0.15	5.3
The Levelized cost of fuel	[Euro/t]	Min.	603.4	1209.0	1063.6	1139.2
		Max.	1137.4	2375.0	1112.8	1889.5
	[Euro/Nm^3]	Min.	0.432	957.5	0.747	968.3
		Max.	0.814	1881.0	0.822	1606.1

Table 11. **Average specific energy resources demand for traditional and electric vehicles [11,18]**

Transport type	Specific gasoline/diesel consumption [l/km]	Specific electricity consumption FCHEV [Wh/km]
Small cars	0.06	109
Large cars	0.09	135
Medium trucks	0.17	276
Large trucks	0.26	422
Buses	0.25	405
Trains	1.92	2600

Table 12. **Specific costs assessment for FCHEV**

Parameters		Value	
Electricity demand for FCHEV [GWh/year]		417.8	
Fuel cells efficiency [%]	Alkaline	63	
	PEM	60	
Annual hydrogen demand [t/year]		10601	
Ratio between small and large cars		3:1	
Average specific hydrogen consumption [kg H_2/km]	Small cars	0.0047	
	Large cars	0.0058	
Annual vehicles total mileage [million km/year]	Small cars	1691.7	
	Large cars	456.9	
Specific investment costs [Euro/MWh]	Storage	0,005	
	Compression	1	
Investments costs [million Euro]	Storage	2088.9	
	Compression	501.4	
Total investments discounted costs [million Euro]		2089.5	
Specific operation and maintenance costs (year 0) [Euro/kWh]	Compression and storage	0.05	
	Logistics and transport	0.1	
Total operation and maintenance discounted costs [million Euro]		331.4	
Hydrogen minimum and maximum cost [Euro/kg]		3.45	10.34
Total discounted costs associated with hydrogen production [million Euro]		239.2	717.3
Total discounted costs [million Euro]		2374.7	2852.8
Specific costs for FCHEV [Euro/km]	Small cars	0.16	0.19
	Large cars	0.18	0.21
Specific costs for traditional vehicles [Euro/km]	Small cars	0.081	
	Large cars	0.121	

Next, it is proposed to assess the required investment for transport electrification and specific costs for FCHEV on example of small and large cars and comparing this cost with that for traditional vehicles. The study period of 10 years is accepted. The calculation and results are presented in table 12. It is accepted the minimum and maximum Levelized Cost of Hydrogen for PEM electrolysis.

The results demonstrate that specific costs for FCHEV are much higher compared to traditional vehicles. For instance, this cost is double for small cars. Table 13 present total discounted costs required for hydrogen integration with the view of energy transition to carbon neutrality of the Republic of Moldova until 2070 [13].

Table 13. **Total discounted costs estimated for green hydrogen integration into national economy**

Scope		Total discounted costs [milliards Euro]	
		Minimum	**Maximum**
Hydrogen production		3.0	10.7
Synthetic fuel production*	Methane	9.7	18.3
	Methanol	0.3	0.7
	Ammonia	0.1	0.1
	Diesel	3.2	5.3
Hydrogen fuel cell electric vehicles*		2.4	2.9
Total		18.8	38.0

* Not include hydrogen production

7. Conclusions

Performed research demonstrates that hydrogen use is viable in the perspective of the energy transition to 100% energy from renewable energy sources. The hydrogen production cost is highly dependent on the electricity source and electrolysis technology. Evident, the Levelized cost of hydrogen and Levelized cost of stored energy can be reduced considerably by the assumption that the electrolysis used with VRES power plant are not designed strictly for the generation graphic flatten and exist the possibility to increase the load factor of the electrolysis.

Even under these conditions, at the lower limit of the cost of hydrogen produced, the storage of energy in the form of hydrogen or the production of synthetic fuels is feasible. The only area that is considerably above the feasibility limit is FCHEV. However, in the current conditions of the dramatic increase in resource prices, dictated by political and economic instability in the region, the use of hydrogen may become more feasible and compete with fossil energy resources.

At the actual stage of development, it is important to reduce the cost of hydrogen production and use equipment, to increase the efficiency of these processes, and of course, to identify required capital resources to begin implementation of required measures for the energy transition.

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