INSIGHTS, PERSPECTIVES AND GENERAL ASPECTS FOR RENEWABLE HYDROGEN DEVELOPMENT IN ROMANIA

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The article intends to provide a picture of hydrogen economy potential in Romania, in the European context. Also, were identified and analyzed some scenarios with opportunities and possibilities for implementing this technology.

The working assumptions taken into consideration the hydrogen production from renewable energy surplus and coverage a part of Romania's natural gas needs. For each situation was calculated hydrogen production cost according with investment and operating costs.

The last scenario depicts a possible infrastructure for hydrogen distribution and storage integrated with both European markets and national electricity and natural gas networks.

Keywords: hydrogen economy, hydrogen storage, renewable hydrogen, HyUnder

1. Introduction

The energy sector is facing with the necessity to store large energy quantities for short to long term in order to adapt to the increasingly intermittent renewable energy. In Romania, energy storage will start to be a subject of obvious importance, both with regard to renewable energy resources and nuclear power.

Hydrogen underground storage at large scale can be expected to support the integration of intermittent renewable energy sources. Important quantities of hydrogen can be produced from renewable electricity by water electrolysis, known also as renewable hydrogen. Hydrogen underground storage in salt caverns at elevated pressures is a suitable candidate for dynamic peak load energy storage and hydrogen can be released within an adequate period of time.

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The report results have originated from European assessment project, named HyUnder, (Fuel Cell and Hydrogen Joint Undertaking, grant no. 303417) and has set out to reveal more about the storage potentials, relevant salt and other relevant underground energy storage geologies, process technology and cavern operating conditions, potential business models and relevant energy markets for use of large scale hydrogen underground storage in Europe [1].

The future hydrogen infrastructure may take years lead time for its development, but, early scientific, technical and business analysis is needed in time, involving representatives of the relevant communities to sharing their know how in an attempt to develop a realistic plot that may help to better understand the role of hydrogen in Romania's future renewable energy based energy system. The percentage of renewable energy in Romania is one of the highest already today; therefore the integration of further renewable energy will require further fundamental changes in the energy system. The hydrogen energy literature includes information about demonstration projects, results of infrastructure development, the energy system impact, industry positions, etc. [2-4].

2. The energy system in Romania and the role of hydrogen

Romanian's energy system has followed its own development strategy in line with the country's own needs, and influenced by European energy policy. In the last time Romania has made considerable progress developing institutions compatible with market economy, and joining the European Union (EU) initiatives towards harmonized energy system transition. The strategies for development of hydrogen and fuel cell technologies vary considerably from country to country, two types of policies were identified: i) policies developed by the European Commission, and supported by Fuel Cells and Hydrogen Joint Undertaking (FCH JU), and ii) policies of the Members States. Romanian Association for Hydrogen Energy has been recently established with nongovernmental organization status, being recognized by international organizations and coming up with a number of initiatives that were included the proposal of Romanian's energy strategy [5].

The contribution of individual energy sources in Romania's recent energy history is a consequence of the past development of the electric power industry in the centrally planned economy. The actual policy has acknowledged the importance of enhancing the efficiency in energy production, in order to protect the environment as well as public health and welfare [6].

Renewables, including hydro, will remain to have an important share for electricity generation/balancing, also in the context of an energy system applying hydrogen as energy vector. In Romania, hydropower covers a large proportion of the electricity production; but also other renewable energy sources are increasingly being tapped. The fastest developing renewable energy technology is wind energy, extending the net electricity generating capacity. In the period 2014-2015 its amount was estimated to be between 12.7% - 15.3% of the Romanian net generating capacity. The gross renewable generating capacity and installed power in 2013 was: hydro 15,104 GWh (6,648 MW), wind 4,721 GWh (2,607 MW), PV 413 GWh (860 MW) and biomass 319 GWh (96 MW) [7].

There are some public universities and research institutes involved in the field of hydrogen and fuel cell research and development in Romania. The active ones have been conducting intensive investigations on a number of issues related to hydrogen energy and particularly about hydrogen storage. Public funding on research and development is available through a national authority subordinated to the Ministry of Education and Research. From estimations, Romanian research authorities have spent about 20 M€ for hydrogen and fuel cell related research (from the year 2000 to the present) [8].

Based on Scopus, we have identified more than 100 sources (articles and reviews) in the field of fuel cell and hydrogen energy from Romanian institutes in this period, covering subject areas such as engineering, materials science, chemistry and chemical engineering, energy, environmental science and mathematics. As a result, Romania ranks in the middle of other neighboring or Eastern European countries. Countries such as Russia, Turkey and Poland have produced more than 300 scientific papers in this field, Greece and Austria more than 100 scientific papers; Hungary, Czech Republic, Ukraine and Bulgaria less than 50 articles per country [9-10].

3. Renewable hydrogen development in Romania

The economic development based on both renewable energy and hydrogen will request three interdependent technologies: renewable and nuclear energy, hydrogen production and fuel cells. This means many challenges to which both society and the scientific community must face. Technical solutions will not be easily found, and financial obstacles associated with these technologies will not be easy to overcome.

3.1. Methodology

The next economic analysis of the renewable hydrogen production follows the joint methodology elaborated in HyUnder project, which has been developed to carry out business case type of analysis at prototype plant scale, is representative for country's / region's conditions and reflect the specific framework conditions.

The system boundaries are defined such that the analyzed cavern plant includes electrolysis, compression prior to the underground salt cavern as hydrogen storage and all topside equipment after the cavern (i.e. hydrogen drying, purification, compression for trailer filling, re-electrification unit and NG grid injection unit). In this context, the analysis does not take into account any infrastructure between the cavern site and the end user (e.g. no trucks for H_2 transportation to hydrogen refueling station).

In general, the modeling approach consists of two major consecutive steps. In the first step each case study analyses the regional potential for hydrogen production and underground storage including geological conditions, existing energy infrastructure at individual sites and future hydrogen demand. This step results in a selection of one or several cavern sites or areas most suitable for hydrogen production and storage. In the second step a techno-economic analysis for a prototypical cavern site is conducted in order to provide an in-depth evaluation of the required investments and optimal site operation resulting in calculation of most important key performance indicators such as net present value of the selected site or specific hydrogen costs [11].

3.2. Scenarios for hydrogen production

The following examples and scenarios will take into account the hydrogen production from renewable energy surplus to cover imported natural gas consumption, the needs of transportation sector and for re-electrification. For these potential situations will be calculated productions capacities, hydrogen requirements and production costs.

In Romania were consumed about 13.5 bcm (billion cubic meters) of natural gas in 2012 [12]. Even though in recent years was recorded a steady consumption, there is expected to increase consumption by 11% for 2020-2025 [13]. Based on previous estimates can be calculated the amount of hydrogen which can be introduced into natural gas pipelines: 12470 t / year (2%), 31,160 t / year (5%) and 62 390 t / year (10%) at the level of consumption from 2012.

In 2025, the wind power production in Romania is expected to have an installed capacity of 4,000 MW. The full operating time is about 2350 hours per year. From this output, a rate of 5-10% can be considered excessive and this amount of energy could be converted to hydrogen, which can be used for re-electrification or other commercial and industrial purposes.

The presented working assumptions are taken from HyUnder project scenarios. Calculations will consider the electric power amount, efficiency of electrolyzers and lower heating value to calculate the hydrogen quantity required (equation 1), or installed power (equation 2). In turn, the obtained values can be adjusted with specific factors which relate to losses during storage, delivery, transportation, etc.

$$H_2[kg] = T[h] \cdot P[MW_{el}] \cdot Ex[\%] \cdot \frac{1000\left[\frac{kWh}{MWh}\right]}{QiH_2\left[\frac{kWh}{kg}\right]} \cdot \eta[\%], \tag{1}$$

$$P[MW_{el}] = \frac{H_2[kg]}{T[h] \cdot Ex[\%]} \cdot \frac{QiH_2\left[\frac{kWh}{kg}\right]}{1000\left[\frac{kWh}{MWh}\right] \cdot \eta[\%]}, \tag{2}$$

where: T, operating time;
P, installed power;
Ex, excess of electricity/power;
QiH_2, lower heating value of hydrogen, 33.33 kWh/kg or 120 MJ/kg;
η, electrolyzer efficiency.

The estimated quantity of hydrogen by authors, for 2025 is presented in Fig. 1. Thus, according to the assumed scenarios, for transportation will required 530 tH_2/year, 19000 tH_2/year will be needed for re-electrification and 69300 tH_2/year for replacement of 10% of natural gas consumption.

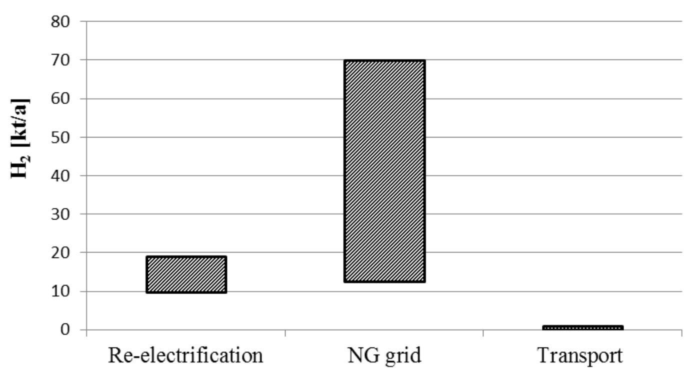

Fig. 1. Scenarios on Hydrogen production in Romania, 2025

The first scenario refers to renewable hydrogen production. The hydrogen necessary, the installed power and the number of electrolyzers are calculated using equations (1) and (2). These calculated values for two operating modalities 1000 h/year, respectively 2000h/year, are shown in Table 1.

Table 1

Electrolyzer requirements and installed power for electrolysis

Operating hours	Indicator	Re-elect.	NG	Transp.	Total
1000 h/an	No. of electrolyzers*	505.00	1861.00	14.00	2380.00
	Electrolyzer power (MW)	2.00	2.00	2.00	-
	Total power (MW)	1010.00	3721.06	27.78	4758.84
2000 h/year	No. of electrolyzers*	253.00	931.00	7.00	1191.00
	Electrolyzer power (MW)	2.00	2.00	2.00	-
	Total power (MW)	505.00	1860.53	13.89	2379.42
* round values					

The results considering total working time for 500 h/year, 1000 h/year 2350 h/year, 3000 h/year and 4000 h/year can be seen in Table 2. This was conditioned by working time of wind turbines and photovoltaic panels, for electricity production and, eventually, the Cernavoda nuclear power plant. As expected the highest amount of electricity will be required for hydrogen production used for gas network. The hydrogen used in automotive applications is small as quantity by comparison with above mentioned needs (electricity and gas).

Table 2

Electrolyzer requirements and installed power for electrolysis depending on annual load

Version	A	B	C	D	E
Complete workload hours (h/an)	500	1000	2350	3000	4000
Annual load (%)	6	12	26	34	46
No. of electrolyzers*	4759.00	2380.00	1013.00	794.00	595.00
Electrolyzer power (MW)	2.00	2.00	2.00	2.00	2.00
Total power (MW)	9517.66	4758.84	2025.04	1586.28	1189.70
Required Energy (GWh)	4758.83				
* round values					

For all five versions, listed in alphabetical order from A to E, the authors calculated the production costs per kg of hydrogen, Fig. 2, using the methodology indicated in bibliography [11].

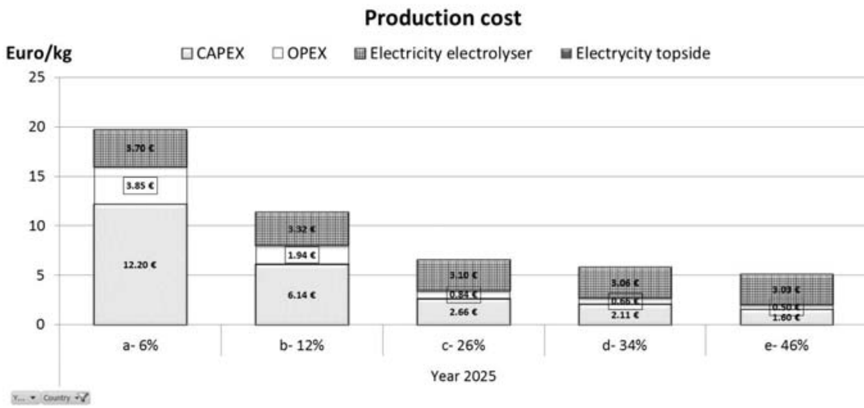

Fig. 2. The hydrogen production cost depending on load

The annual load was calculated as a ratio between the number of operating hours, full load, and the total working hours for electrolyzers during one year: 8760 hours.

A second scenario relates to the hydrogen production to cover part of Romania's natural gas needs to reduce import dependency and decrease carbon dioxide emissions. For three variants work, covering 5%, 10% and 20% of the necessary, the production cost was calculated inclusive for variant that is not required seasonal storage of hydrogen in salt caverns. In this scenario was considered a full workload for operating electrolysis plants, about 8760 hours annually.

Table 3

Scenarios for hydrogen production to cover 5%, 10% and 20% of natural gas consumption, the hydrogen production cost

Version	NG 5%	NG 10%	NG 20%
Full load hours (h/year)	8760	8760	8760
Total power (MW)	215.56	427,94	852,72
No. of electrolyzers	107.78	213,97	426,36
Electrolyzer power (MW)	2.00	2,00	2,00
Energy required (GWh)	1888.31	3748.75	7469.83
Hydrogen cost with underground storage (Euro/kg)	4.77	4.66	4.57
Hydrogen cost without underground storage (Euro/kg)	4.51	4.50	4.50

The price for hydrogen production was calculated, by authors, for three cases as follows: 4.57 Euro/kg, 4.66 Euro/kg and 4.77 Euro/kg, where renewable hydrogen covers 20%, 10%, respectively 5% of natural gas consumption at national scale. Considering the situation when would only take into account operating and amortization costs for electrolysis installations and equipment, and would eliminate storage in caverns, both investment and operating costs, the hydrogen production cost for all three situations will range between 4.50-4.51 Euro/kg, Table 3, Fig. 3.

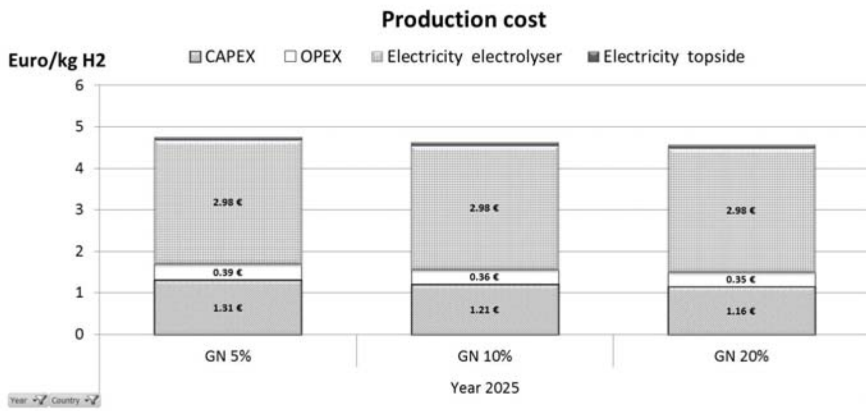

Fig. 3. Hydrogen production cost to cover 5%, 10% and 20% of natural gas consumption.

Previous scenarios contain calculations based on assumptions which could be considered improbable, at least at this moment, when we refer to electrolysis capacities which can totalize 4758.84 MW or 9517.66 MW. As a complement to above mentioned it should be noted that for the short and medium term, Romanian energy strategy, along with development of hydro pumping storage capacity to 1000 MW, provides an increase of 50% natural gas storage capacity and oil and petroleum products storage capacity will covering 67.5 days of annual consumption, reference year 2011, so the scenarios which refer to electrolysis installations up to 2000 MW for energy storage and reconversion are plausible [14].

As already has been mentioned in other works of authors, the economic assessment of the technology requires the estimation of the hydrogen demand in each of the case studies of the HyUnder project in both time horizons established for the assessment, 2025 and 2050. In order to evaluate the hydrogen demand we should difference among hydrogen potential additional demand (a hydrogen demand that currently does not exist), that will come from the transport sector, re-electrification and power to gas applications, for the last one we also have to consider technical limits of the injection of hydrogen in the NG grid, and hydrogen substitution demand, hydrogen currently produced mainly by natural gas reforming and already used in the industry [15].

3.3. Scenario for a renewable hydrogen infrastructure

Today, the hydrogen is mainly used by chemical industry, in refineries and for ammonia production and production has so far been dominated by reforming of hydrocarbons [16].

The gradual hydrogen transition into the energy market could be assimilated by incipient hydrogen communities, also in early niche markets, both for its stationary use and use for transport as a vehicle fuel. In the context where hydrogen will become an energy vector together with electricity, it can be obtained from a number of resources and by various processes, in the future more and more dominated by renewable technologies. Certainly, technologies must take into account both aspects of ecology and economy.

A mature hydrogen economy will assume not only the existence, but also the continuity of centrally organized energy systems, the introduction of hydrogen into the energy systems, the hydrogen distribution grid development for transferring hydrogen from the production locations to the consumption sites. As part of this infrastructure, hydrogen storage would play an integral and important role. Today thousands kilometers of hydrogen pipelines are in operation around the world which supplies chemical plants or refineries. The experts assume that the development of a centralized hydrogen pipeline transport and distribution network could take as long as 60 years and the centralized infrastructure could cost half of a decentralized hydrogen infrastructure [17].

Hydrogen could be supplied for vehicles, via (national) refueling station networks, industry and residential sectors for electricity and heat requirements. For the success of the hydrogen economy, secure and cheap hydrogen infrastructures will be need. The balance between use of hydrogen onsite and storage of hydrogen from distribution network will be dictated by both the complementarity of supply and demand as well as possibly regulations as well as geographic conditions. The future energy system will be developed with two energy provision networks in place, one for electricity and one for hydrogen, using power-to-gas technology (electrolysis) or something derived from it (e.g. synthetic methane gas through methanation with CO_2).

The hydrogen network can be designed somewhat similar to electric transmission grids or natural gas ones. The hydrogen network would comprise two subsystems: one for transport and one for distribution, the first one including a transmission ring, Fig. 4, the sites where is possible to locate the large scale hydrogen underground storage facilities in Romania are necessary to intersect this hydrogen transition ring. In this way the storage facilities will be well connected to the national hydrogen network. Details about those potential sites, four by number, already were described in other works. The infrastructure will include, in addition to large scale hydrogen underground storage facilities, numerous plants or devices and will make the system operational: hydrogen production plants, especially electrolysers with renewable electricity; supply stations; maintenance services; connections with renewable and electrical grid; fuel cell plants; control and operating centers; stations for import-export; small scale storage facilities etc. One possible future part for this infrastructure also can be hydrogen production from nuclear energy [18].

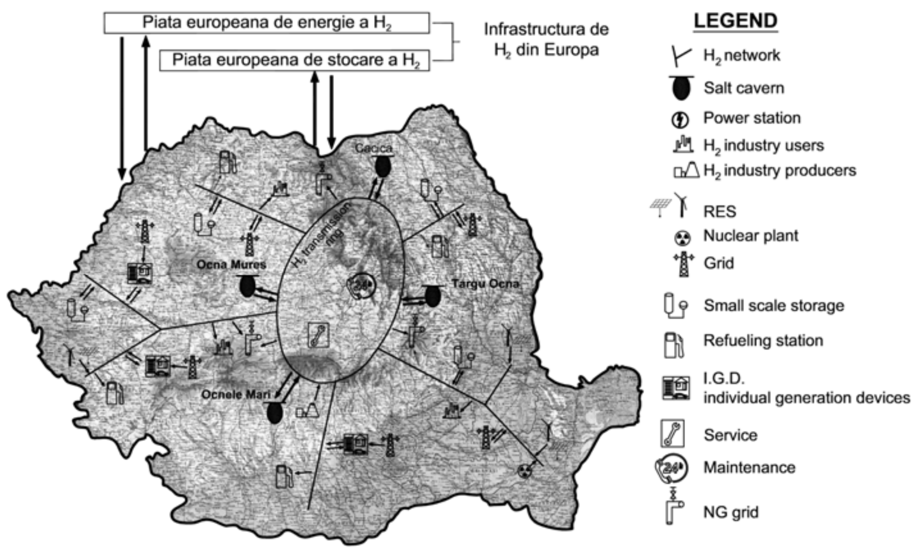

Fig. 4. Scenario for a hydrogen infrastructure in Romania, source [15].

The hydrogen network would then be connected to the European market; national operator(s) can export or import hydrogen. There is imperative to understand that hydrogen can be exported and imported both as energy vector and stored energy. In the future, the sale of energy storage can be a distinct market, so the large scale hydrogen underground storage will have a multifunctional role and the benefits will be comprehensive.

4. Conclusions

The plausible increase in the deployment of renewable energy sources, most notably wind and solar, will lead to a considerable amount of electricity production for which there is no immediate demand. Energy storage will be necessary to prevent negative effects of fluctuating renewable electricity system. The surplus of electricity generated could be stored via hydrogen underground storage, through electrolysis, thus offering not only the possibility for the reverse path back to power (i.e. classical "electricity storage"), but also the possibility to integrate wind and solar energy into the energy system beyond the electricity system in sectors as transport, natural gas and the industry.

A geologic mapping of European regions for underground storage of hydrogen has been developed in the HyUnder project. The analysis was focused on salt caverns and the obtained results conclude that hydrogen underground storage is geologically feasible, including Romania. The geologically features to realize the cavern, vicinity to transport needs, vicinity to fluctuating energy sources (sufficient voltage level), vicinity to H_2 pipelines, vicinity to NG consumptions and industrial consumptions, vicinity to HV power grid and NG nodes and the number of locations have been considered as the key parameters to assess the different sites with renewable potential.

Throughout its evolution, hydrogen economy, including both production and storage, will inevitably lead to the birth of the national infrastructures, even European. Part of those infrastructures will certainly be: pipelines and connections, storage facilities, refueling stations, hydrogen individual devices, services, maintenances.

However, the article deals only in terms of renewable hydrogen. Authors discuss other items, general or specific on the other works.

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