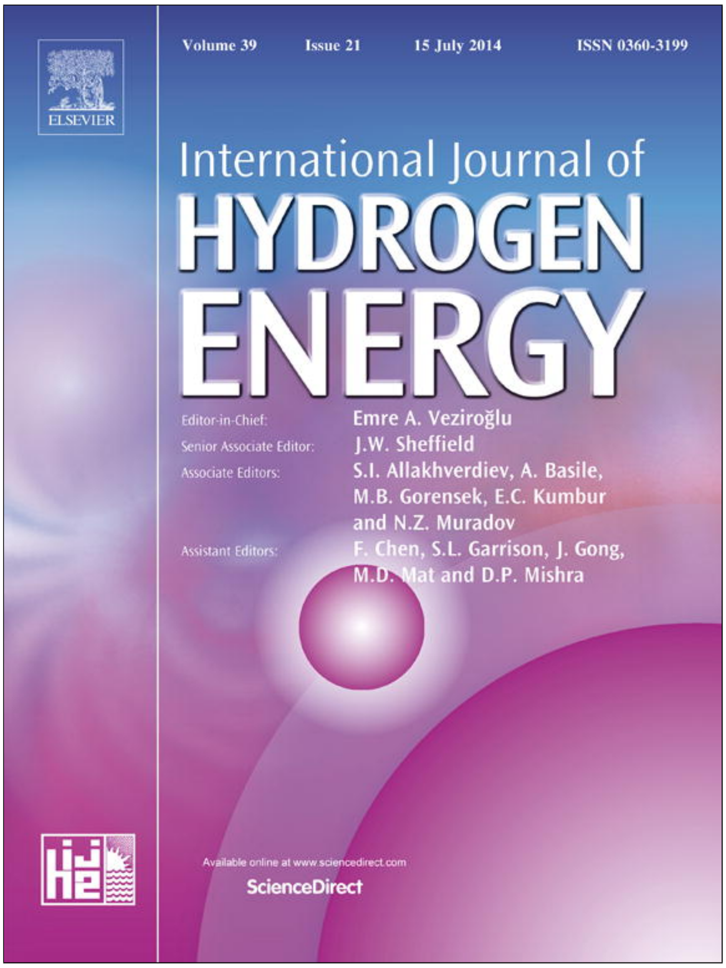
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Hydrogen underground storage in Romania, potential directions of development, stakeholders and general aspects

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ABSTRACT

Romania is a country with relatively good opportunities to manage the transition from the dependence on fossil energy to an energy industry based on renewable energy sources (RES), supported by hydrogen as an energy carrier. In order to ensure Romania's energy security in the next decades, it will be necessary to consider a fresh approach incorporating a global long-term perspective based on the latest trends in energy systems. The present article focuses on an analysis of the potential use of salt caverns for hydrogen underground storage in Romania. Romanian industry has a long technical and geological tradition in salt exploitation and therefore is believed to have the potential to use the salt structures also in the future for gas and specifically hydrogen underground storage. This paper indicates that more analysis works needs to be undertaken in order to value this potential, based on which macroeconomic decisions then can be taken. The present work examines the structures of today's energy system in Romania and features an analysis of Romania's current potential of hydrogen underground storage as well as, reports on the potential use of this hydrogen in chemical industry, the transport sector and salt industry in Romania and highlighting issues implied by a possible introduction and use of hydrogen and fuel cell technologies.

Introduction

Romania's energy sector is facing the need to store extremely large energy quantities for short to long-term (days to weeks) in order to adapt to the increasingly intermittent renewable energy production. In Romania, energy storage will become a subject of obvious importance both with regard to renewable energy resources and nuclear power. One potential flexibility option for the power sector is the use of large scale energy

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storage, storing the energy produced mostly as electricity in periods of surplus for later use during times of peak demand. Today, pumped hydro schemes are the preferred technical solution due to its favorable economics, but, as these are limited in potential, in the long-term, energy storage schemes with considerably higher energy storage capacities will be needed.

Hydrogen storage at large scale can be expected to support the integration of intermittent renewable energy sources in the current energy system. Large quantities of hydrogen will be produced from renewable electricity through the electrolysis of water, known also as green hydrogen. Hydrogen storage in salt caverns by a large pressure differential and at elevated pressures is a suitable candidate for dynamic peak load energy storage and hydrogen can be released within an adequate period of time. The salt caverns are highly impermeable for hydrogen even under high pressures and are virtually leak proof. The cushion gas requirements for the hydrogen storage are large and depend on the minimum possible cavern pressure, but are defined as economic inventory, and hence are part of the total capital expenditure [1].

Early open literature references about hydrogen underground storage were made in 1976 [2], respectively 1979 [3]. These publications reported on analysis work on physical, chemical, environmental and energy issues, all in the context of large scale energy storage. In the same period of time a major study on the same topic was conducted by the Institute of Gas Technology, USA [4]. A few years later, other groups of researchers also discussed issues related to technical and economic aspects. In the latter source, a scenario about hydrogen underground storage in salt caverns in connection with the use of renewable energy has been laid out for the first time, by presenting a hydrogen underground storage scheme for balancing out tidal energy fluctuations [5]. Other groups disclosed a conceptual design for compressed hydrogen storage in mined caverns, i.e. in excavated tunnel-shaped caverns [6]. At that time hydrogen underground storage appeared to be the most promising solution to the problem of large scale energy storage which seems to be learnt a fresh today. Despite the principle idea of large scale hydrogen underground storage in salt caverns is already three decades old, much work remains to be done to put real systems into operation and demonstrate their effect. This paper intends to contribute a basis for a potential future implementation strategy.

Having disappeared from literature for about 15 years, in 2000 the idea of hydrogen underground storage reappears. Some sources disclose relevant comparisons between hydrogen underground storage and high-pressure overground storage [7], the potential of large scale hydrogen storage in the UK [8], the USA [9], Denmark [10,11], Germany [12] and Russia [13]. Also one study has reported about a possible integration of large scale hydrogen underground storage into European energy infrastructure [14].

The work for this report has originated from an ongoing European assessment project by the name of HyUnder. HyUnder is supported by the FCH JU (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 the use of large scale hydrogen underground storage in Europe. Romania is one out of six regions serving as prototypical energy market with sufficient salt structures. More about the project can be found on the project webpage, www.hyunder.eu. In HyUnder project, 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 (i.e. hydrogen drying, purification, compression for trailer filling, re-electrification unit and NG grid injection unit).

Today, a number of industrial hydrogen underground storage applications are in operation. Chemical industry is operating hydrogen salt caverns in Clemens and Moss Bluff in the U.S., as well as in Teesside in the UK, where hydrogen is stored in three small and shallow caverns, using pumping of brine into above ground brine ponds instead of differential pressure for hydrogen storage underground. In all three cases the stored hydrogen is used in chemical industry and not as an energy vector. Also, in the past, hydrogen has successfully been stored underground in France, Germany and former Czechoslovakia, as pure hydrogen for aerospace industry needs in Russia, or as town gas: a gas mixture including hydrogen (40–60%), carbon monoxide, methane and volatile hydrocarbons [15].

Another section of this paper develops an actual snapshot of the Romanian energy system and at the potential role hydrogen might play in it, for storage and end-use. A future hydrogen (storage) infrastructure may take years lead time for its development. Therefore, 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. Even though the share of renewable energy in Romania is one of the highest already today, the consequences of an integration of further renewable energy will require further fundamental changes in the energy system. The best approach to develop this pathway is by developing the transition using both a long-term and short-term forecast (backcasting/forecasting approach). Romania has a long tradition (more than 2000 years) of salt extractions. Today, Romania operates several active mines, but some older mines have also been closed. Many of these sites may have the potential to be used for hydrogen storage to form part of a wider hydrogen infrastructure.

Overview of the energy system in Romania and the potential role of hydrogen in it

Romanian's energy system has followed its own development strategy in line with the country's own needs, but also influenced by European energy policy. As such, a potential evolution of the role of hydrogen in the energy system will have an impact on the Romanian energy system.

The hydrogen energy literature includes details of demonstration projects, results of infrastructure development economics and cash flow analysis, the environmental and energy system impact, industry positions, etc. [16,17]. In the last 20 years Romania has made considerable progress developing institutions compatible with a market economy, and joining the European Union (EU) initiatives towards harmonized energy system transition including hydrogen as an energy carrier. European national strategies on the 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, also further divided into national and regional policies.

The objective of the Romanian energy policy is to ensure energy security, which guarantees continuous, stable economic growth to cover the required domestic consumption of electricity and heat under constraints of sustainability policy goals (e.g. reduction of greenhouse gas emissions, energy diversity and de-carbonization; reduction of particulate emissions, etc.). Other requirements include the gradual liberalization of electricity markets and a policy promoting sustainable development, e.g. by building on energy savings and improvement of energy efficiency by technology improvements. These major three goals are referred to as the 20-20-20 policy for 2020, which implies a 20% reduction in greenhouse gas emissions, a 20% reduction in energy consumption, and a 20% increase in the contribution of renewable sources. Concerning the last goal, Romania has a more ambitious goal of reaching 24% by 2020.

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 (see Ref. [18]).

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 share 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 share was estimated to be between 12.7% and 15.3% of the Romanian net generating capacity. The gross renewable generating capacity and installed power in 2013 was: hydro 15,104 GWh (6648 MW), wind 4721 GWh (2607 MW), PV 413 GWh (860 MW) and biomass 319 GWh (96 MW) [19].

Romanian authorities have not yet adopted any program (e.g. a roadmap including hydrogen as energy carrier) that would specify objectives and assignments or integrate and coordinate the individual activities. In Europe, Germany, the UK, France, the Netherlands, Norway and Denmark, and worldwide the USA (California), Japan and South Korea have positioned themselves as leaders in the development and implementation of hydrogen and fuel cell technologies. Romania is a country with relatively good opportunities to manage the transition from a dependence on fossil fuels to a renewable based energy system using both electricity, synthetic methane gas and hydrogen as complementing energy carriers in the view of a wide application in energy end-use The decision to replace these systems would offer an opportunity to implement fuel cell stacks instead of actual technologies, or to use hybrid systems that combine conventional and modern methods of electricity generation.

There a number of public universities and research institutes in Romania, with only few of them being involved in the field of hydrogen and fuel cell research and development. 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 our estimation Romanian research authorities have spent more than 20 M€ for hydrogen and fuel cell related research (from the year 2000 to the present).

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.

In Romania 13 industrial hydrogen producers could be identified [20]. The hydrogen market comprises two major players: captive producers which produce hydrogen for their direct (i.e. onsite) customer or their own use and by-product hydrogen resulting from chemical processes. In Romania, hydrogen is consumed by mainly two industrial sectors: the refinery and the ammonia industry, which are both captive users. Besides the two categories of manufacturers, petrochemical and agrochemical, there is a third category chlor-alkali industry, where hydrogen is generated as by-product during brine electrolysis.

Building a coherent roadmap, both for hydrogen and fuel cell technology, with regard to the EU as a whole and for its individual member states, seems to be a difficult task. Some countries are more willing to prepare for changes than the others. Countries experiencing major economic challenges, including the new EU Member States, will have different expectations in financing and implementing an introduction of hydrogen into the energy system than the affluent ones [21–24].

A strategy for Romania must take into account the geopolitical factors that affect it, its state of economic development and the social awareness for the potential wider role of hydrogen in the energy system. A hydrogen roadmap would set the direction for the required changes, could feature future stages in logical succession, and its timeframe. As a general remark, it is observed that countries that are facing obstacles in promoting and implementing hydrogen technologies widely typically tend to develop ambitious plans rather than realistic ones; Romania is no exception. Adequate funding and decision of experts are key elements for the success implementation of such a hydrogen research program.

Romania participates in the European Hydrogen and Fuel Cell Platform (HFP) and HY-CO ERA-NET project and is active in the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). Romania has also expressed its concerns for dedicated actions and/or to put into place specific mechanisms in order to narrow the current gap between the western and eastern part of Europe in the area of hydrogen and fuel cell research.

As already was mentioned (see Ref. [25]), some industrial processes stick out for Romania which may be used to obtain or to use sustainable hydrogen: steam methane reforming with carbon capture and sequestration, hydrogen from biomass and bio-hydrogen, hydrogen produced from renewable electricity by electrolysis of water, nuclear hydrogen and hydrogen for energy storage. The last option is the subject of this work.

The introduction of hydrogen into the Romania energy market offers the possibility to provide a number of advantages: sustainable energy development, valorization of local resources and economic competitiveness. Nevertheless, a number of considerable challenges remains and these are unlikely to be overcome without serious additional effort of both central authorities and industry.

Scenario for a hydrogen infrastructure and network in Romania

At the moment, hydrogen is used mainly by chemical industry, in refineries and for ammonia production and production has so far been dominated by reforming of hydrocarbons, pyrolysis and co-pyrolysis. In the future, hydrogen will become an energy vector together with electricity. Because the hydrogen is most abundant energy in the universe, it can be obtained from a number of resources and by various processes, in the future more and more dominated by renewable technologies. Of course, technologies must take into account both aspects of ecology and economy.

Ideally, the emergence of hydrogen into the energy system would be a decentralized one, with decentralized or even onsite hydrogen production units emerging, essentially as prototype or for demonstration projects. The gradual transition of its wider integration into the energy market hydrogen 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. A respective strategy development is typically for forward countries or regions which exercise also a long-term forecasting approach, involving all parts of the energy system. However, our observations from HyUnder make us believe that a monolithic approach to incorporate hydrogen in the individual energy markets in Europe may not be expected.

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 development of a hydrogen distribution grid for transferring hydrogen from the locations of production to the sites of consumption. As part of this infrastructure, energy and hence hydrogen storage would play an integral and important role. Today thousands of hydrogen pipeline kilometers are in operation around the world which typically supplies chemical plants and refineries. These pipelines have 25–30 cm diameter and operate at 1–5 MPa, but if required pressures of up to 10 MPa can be operated safely using the relevant materials. Some authors 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 [26].

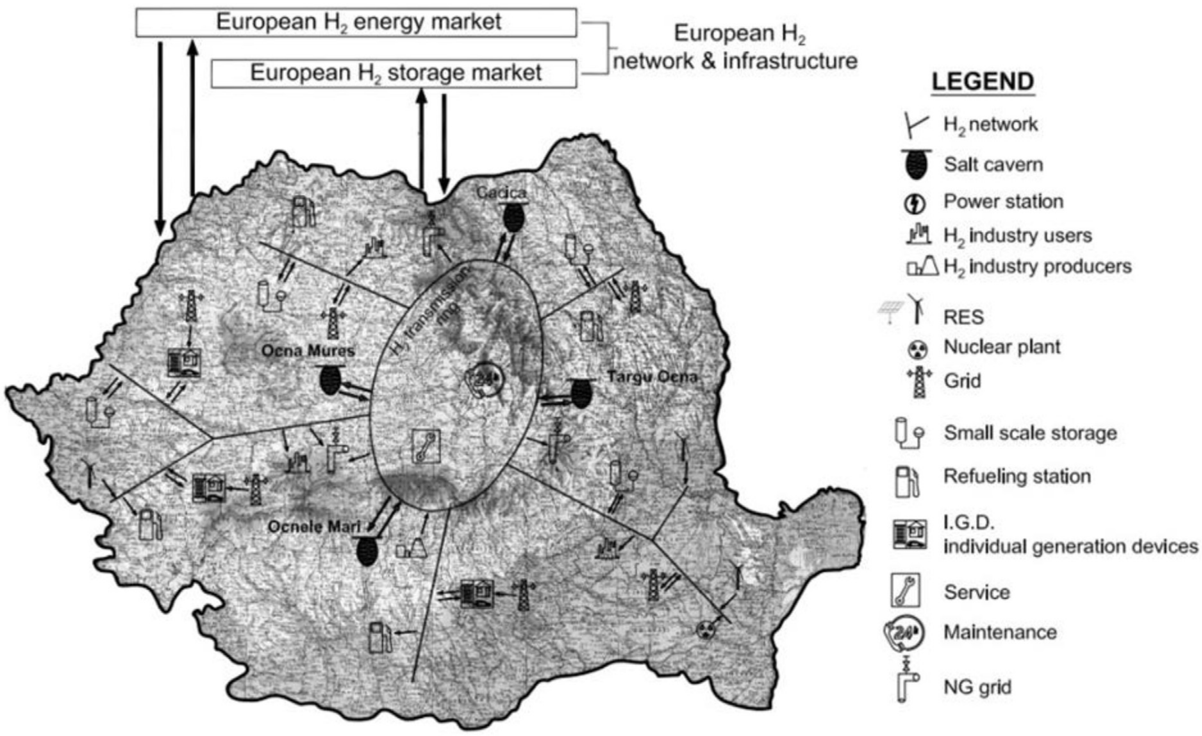

Fig. 1 – Scenario for a hydrogen infrastructure in Romania.

Hydrogen could be supplied both for vehicles via (national) refueling station networks and to the industrial 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. Ideally, a 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. In our proposal, Fig. 1, the hydrogen network would comprise two subsystems: one for transport and one for distribution, the first one including a transmission ring. The potential sites where is possible to locate the large scale hydrogen underground storage facilities in Romania must intersect this hydrogen transition ring. In this way the storage facilities will be well connected to the national hydrogen network and will respond exactly to the global system requirements. Details about those potential sites, four by number, will be described in the next subchapter. This infrastructure will include (Table 1), 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 (aboveground or buried) storage facilities etc. One possible future part for this infrastructure also can be hydrogen production from nuclear energy [27].

To allow a market compatible operation of this hydrogen supply and demand scheme, free of regulatory delimitations to the largest possible extent, precautions need to be taken for building and operating.

This national hydrogen network would then be connected to the European market; national operator(s) can export or import hydrogen. It is imperative to understand that hydrogen can be exported and imported both as energy vector and stored energy. In the near future, the sale of energy storage will become a distinct market. In this context it is obvious as large scale hydrogen underground storage will have a multi-functional role and the benefits will be comprehensive.

Reiterating the opinion of some authors cited in this work, this can be considered a brief description of what is pursued by visionaries who believe in a hydrogen-based future.

Large scale hydrogen underground storage in Romania

Method of selection of early hydrogen underground storage sites

With more than 2000 years of salt extractions, Romania has a long tradition in this cavern development and operation. Nowadays, Romania has 7 active sites, both mines and

Table 1 – Main elements for a national hydrogen network and infrastructure.

Nr.	Element	Brief descriptions
1	Hydrogen pipeline transport and distribution	Used to transport hydrogen from the point of production to the point of demand. The technology for hydrogen pipeline transport is proven and the transport costs are somewhat above those for natural gas pipelines.
2	Transmission ring	As integral part of hydrogen pipeline transport contributes to system flexibility and connectivity.
3	Large storage facilities (underground)	This study has only addressed salt caverns, in principle other geological formations may also be used.
4	Connections	Include all direct and indirect contacts with hydrogen producers and users: industry, RES, natural gas and electric grid, refueling stations, etc.
5	Hydrogen refueling stations	Storage or fueling stations for hydrogen are usually located along a road or hydrogen highway, or at home as part of the individual generation device.
6	Small scale storage	Hydrogen can be stored above ground in a gasholder largely for balancing (making sure pipes can be operated within a safe range of pressures), not long-term storage.
7	Hydrogen individual generation devices	In dedicated electrolysers able to produce hydrogen for individual houses and cars. These devices will be able to produce hydrogen when, for example, electricity price is low or to be connected to a neuronal network that can order hydrogen production conditioned by algorithms.
8	Intersections with European infrastructures	National infrastructure will have connections with neighboring countries as part of the European network and infrastructure. There is the opportunity to participate in European hydrogen energy and storage markets.
9	Services and maintenance	These are necessary elements for the operation of technical systems.
10	Nuclear hydrogen	The utilization of nuclear energy for large scale hydrogen production is believed to have a key role in a sustainable energy future in Romania. Co-generation of both electricity and hydrogen from nuclear plants may become increasingly attractive. The nuclear hydrogen production mainly includes electrolysis and thermochemical cycles.

caverns. Many of these locations have the potential to be used for hydrogen storage.

The scope is to identify the most promising sites for early hydrogen caverns specifically from a market perspective. It was decided to only consider sites where salt caverns and necessary infrastructure such as a standard procedure for brine disposal already exist. It is much easier to decide the development of the existing fields by conversion of existing caverns or adding new ones for hydrogen storage. The European project HyUnder marks the beginning of Romanian studies related to the possibilities of hydrogen underground storage in our country which aim to acquire information about underground storage of hydrogen and to achieve data about the potential of the renewable energy and energy infrastructure.

A realistic method of selection is useful in order to (1) understand the potential relevance and scale of underground storage of hydrogen as a means for large scale storage of intermittent renewable electricity in the context of the expected development of the Romanian power sector until 2050, (2) identify the most promising sites for potential hydrogen caverns taking into account the specific geological conditions in Romania as well as other relevant location factors, and (3) analyze the economic attractiveness and potential business case for underground hydrogen storage with respect to the different end-use applications of hydrogen (mobility, industry, admixture to the natural gas grid or re-electrification).

Four potential sites have been identified for hydrogen storage: Ocna Mures, Targu Ocna, Ocnele Mari and Cacica, (see Table 2). In all four locations, hydrogen can be produced by water electrolysis in case of renewable energy surplus and when, undesirable situations, demand are less than production. Into this manner important quantities of energy can be saved and stored.

Assessment of the potential hydrogen underground storage in Romania

To understand the potential use of large underground salt caverns for the storage of hydrogen as an energy carrier in Romania, it is important to understand the interest and possible role of the different industry sectors. Though the general interest of each sector follows similar structures, the views or interests of individual companies will differ from each other. The general interest expressed in this article has been compiled by authors and has been reviewed by the individual Romanian stakeholders. The results do not necessarily express the views of any one singular contributing company, but instead the voice of a group of diversely acting specialists, all individuals being experts in their specific application area of hydrogen energy or the use of underground caverns for other industrial purposes in general.

The use of hydrogen to balance the electricity supply system is no new item for discussion among scientists, especially considering the possibility of energy storage in the context of renewable electricity. Also, an official statement by Romanian authorities or regulators is not possible because the national strategy has not yet been clearly defined, but numerous opinions of individuals from both public and private entities underline the idea that renewables and hydrogen will contribute to large scale energy storage, without any single individual or group providing any time horizon. The interest, demand and possible role of hydrogen as an energy carrier for different industry sectors in Romania can follow a few directions like: (1) fuel for transport, like "premium" segment due to willingness to pay a premium for green hydrogen, (2) chemical raw material for industry (refineries and ammonia), (3) injection in natural gas grid, (4) re-electrification and load management in the electricity grid.

Automotive industry is aware that several alternative infrastructures are not desired as they raise total costs of ownership or should at least be limited to a minimum, which makes liquid conventional type fuels the favorite, and also that e-mobility will gain an important role in future individual transport. Major automobile industry has joined forces at regional and international level to prepare private-public frameworks for risk sharing, also building on policy support for the transition period until a functioning market has been established. Automotive industry plays an observing role in hydrogen underground storage. Yet, it could also serve as potential enabler for the introduction of hydrogen into other markets.

Nowadays, Romania does not have a fleet of fuel cell electrical vehicles with hydrogen (FCEVs), except two versions of mobile hybrid electric-hydrogen platform designed, build and used for experiments within various projects at National Center for Hydrogen and Fuel Cell. Romania has introduced incentives for electrical vehicles in its legislation, which has however not been fully enabled, partly due to the financial crisis. In April 2011, new policies were adopted to promote clean and energy efficient road transport vehicles (hybrid and electric). These have been implemented in two ways: grants for purchase and a scrap-page scheme for public administrations or institutions, individuals, NGOs or SMEs. So, there are premises for alignment at EU policies in the field of automotive and environmental protection in the next years [28].

An analysis conducted in 2011 [29] mentions a FCEVs penetration of 5%–50% of the European passenger car fleet by 2050. Translated to the Romanian passenger car fleet of 6.4 M vehicles in 2050, this corresponds to 0.32 M (5% penetrations) to 1.6 M (25% penetrations) FCEVs. Following the same trend as in the analysis given above for 2020/25 is proposed less than 0.1% FCEVs penetration scenario, 0.005 M vehicles. The authors reached these figures taking into account the previously mentioned references, and market-specific aspects of Romania: number of new cars, the fleet age, trademarks weight, prices, etc. [30]. According to the same publication about the power trains portfolio for Europe and hydrogen demand by the mobility sector in Germany, the authors assumed the following scenarios: 11,000 km/14,000 km annual mileage per year with two options regarding the consumption of hydrogen 0.95 kg H_2/100 km and 0.54 kg H_2/100 km in 2020/25 and the same options regarding the consumption of hydrogen but with two limits of penetration, as denoted above, in 2050. Taking into account the previous assumptions (number of cars, kilometers per year and consumption) the authors calculated for automotive application hydrogen consumption in Romania between 297 tons/year in 2020/25 to 211,445 tons/year in 2050.

Table 2 – Sites evaluation, potential locations for hydrogen underground storage in Romania.

Region	Comments	Site	Comments on individual sites
Centre	• Located in central Romania • Close to urban centers such as Cluj Napoca, Brasov, Sibiu	Ocna Mures	• Good geological conditions • Cavern field in conservation • Brine operating infrastructure available • Uncertain demand for brine, a single customer for brine
East	• Located in the eastern part of Romania • Close to urban centers as Bacau, Piatra Neamt, Brasov	Targu Ocna	• Good geological conditions • Cavern field in operation • Brine operating infrastructure available • Brine consumption by local industry
South	• Located in the south of Romania • Close to urban centers as Pitesti, Craiova, Sibiu • Good connections with Bucharest	Ocnele Mari	• Good geological conditions • Cavern field in operation • Brine operating infrastructure available • Brine consumption by local industry • Operator is interested in the Case Study • Romanian National Hydrogen & Fuel Cell Centre in close proximity
North	• Located in the northern part of Romania • Difficult connection to major cities	Cacica	• Good geological conditions • Lack of large caverns, and implicitly appropriate infrastructure

Table 3 also indicates more scenarios for hydrogen consumption by the automotive sector. To determine the expected sales quantity of hydrogen as vehicle fuel, the number of cars could be a good indication. By defining a certain radius around a potential location and comparing the number of cars registered today, (see Table 4), could be used for an extrapolation of a future hydrogen demand for FCEVs. For Romania, it was assumed to have two delivery radiuses for early caverns, 100 km and 200 km.

For chemical or other industry, producing and consuming hydrogen already at very large scale, and in command of all necessary technologies and processes, hydrogen is solely treated as a commodity. Its production, distribution and end-use are driven by costs in the first place. The reduction of GHG emissions are important goals for the hydrogen consuming industry, driven by tightening public constraints and regulations (e.g. CO_2 certificates). There is still a distant future until Romanian industry will start to investigate potential synergies by offering their know-how and existing infrastructures to utilize economic synergies for reducing infrastructure costs on one side and to introduce "green hydrogen" on the other side.

For the hydrogen consuming industry the short-term economic benchmark is the production of hydrogen by steam methane reforming (SMR) or available chemical by-product (chlor-alkali industry).

Table 3 – Hydrogen demand for transport by certain radius around a potential underground storage sites.

Site	Hydrogen consumption (tons/year)					
Year (penetration)	2020/25 (<1%)		2050 (25%)		2050 (5%)	
Radius around site	200 km	100 km	200 km	100 km	200 km	100 km
Scenario 1: 11,000 km per year and 0.54 kg H_2/100 km						
Ocna Mures	142.00	47.00	45,619.00	15,206.00	9123.00	3041.00
Targu Ocna	169.00	41.00	54,172.00	13,305.00	10,834.00	2661.00
Ocnele Mari	201.00	44.00	64,627.00	14,256.00	12,925.00	2851.00
Cacica	98.00	35.00	31,363.00	11,404.00	6272.00	2280.00
Scenario 2: 11,000 km per year and 0.95 kg H_2/100 km						
Ocna Mures	250.00	83.00	80,256.00	26,752.00	16,051.00	5350.00
Targu Ocna	297.00	73.00	95,304.00	23,408.00	19,060.00	4681.00
Ocnele Mari	355.00	78.00	113,696.00	25,080.00	22,739.00	5016.00
Cacica	172.00	62.00	55,176.00	20,064.00	11,035.00	4012.00
Scenario 3: 14,000 km per year and 0.54 kg H_2/100 km						
Ocna Mures	181.00	60.00	58,060.00	19,353.00	11,612.00	3870.00
Targu Ocna	215.00	52.00	68,947.00	16,934.00	13,789.00	3386.00
Ocnele Mari	257.00	56.00	82,252.00	18,144.00	16,450.00	3628.00
Cacica	124.00	45.00	39,916.00	14,515.00	7983.00	2903.00
Scenario 4: 14,000 km per year and 0.95 kg H_2/100 km						
Ocna Mures	319.00	106.00	102,144.00	34,048.00	20,428.00	6809.00
Targu Ocna	379.00	93.00	121,296.00	29,792.00	24,259.00	5958.00
Ocnele Mari	452.00	99.00	144,704.00	31,920.00	28,940.00	6384.00
Cacica	219.00	79.00	70,224.00	25,536.00	14,044.00	5107.00

Table 4 – Estimated numbers of car today and percentages, defining a certain radius around a potential location.

Site	200 km radius around site		100 km radius around site	
	Number	Percentage (%)	Number	Percentage (%)
Ocna Mures	2,548,730	48	849,590	16
Targu Ocna	3,026,620	57	743,370	14
Ocnele Mari	3,610,700	68	796,480	15
Cacica	1,752,250	33	637,180	12

Number of cars today in Romania [30]: 5,309,856 (100%).

Romania accounts for about 1.8% of total European petroleum refining capacity. The official oil needs prognosis for Romanian is about 11.0 million tons for the refinery sector in 2020. This amount will be slightly higher than 2011, but comparable with 2009 [31]. In the long-term (2050), hydrogen demand from refineries might further increase, but depending on the availability of inexpensive crude oil and the demand for petroleum products hydrogen demand could also decrease. Because there are no signs for new investments capacities, except modernizations, we suppose that the refining capacity will remain constant, 15.0 million tons in 2012 [32]. According with revised literature, for this size of refining capacity, a typical hydrogen requirement will be about 75,000–120,000 tons/year [33]. Another hydrogen consuming industry is the one for ammonia and fertilizer production. Ammonia is produced at six plants; in Romania and at this moment the nitrogen production is estimated at 1100 thousand metric tons [34]. From the reaction stoichiometry can be deduced that the need for hydrogen is about 235,000 tons/year for this agrochemical industry needs. At European level, according to European Fertilizer Manufacturers Association, a relative small increase of the consumption is expected for the next decades [35]. So above mentioned amount of hydrogen is considered constant.

Romanian natural gas industry is a mature one; the total length of pipelines is 53,666 km, from where the National Gas Transmission Company (Transgas S.A.) operates a network of 13,000 km. In this industry 41,391 persons are employed and approximately 3,122,000 customers are served including domestic and non-domestic ones (industrial, commercial and other). In 2011, natural gas sales by sector were: industry 44.8% (67.6 TWh), residential 27.9% (42.0 TWh) and power plants 23.4% (35.3 TWh) from a total of 150.8 TWh, with a growth of 3% compared to 2010 [36].

Depending on the future development in this field, an important increase of possible demand for renewable hydrogen could develop, depending on admixture rates now being scrutinized. According with already mentioned statistics, from total amount of natural gas, residential represents 27.9% and power plants 23.4%, this means that 51.3% of natural gas is burned; this portion can be mixed with hydrogen. Taking into account the technical aspects, it is reasonable to assume that the injection of hydrogen for domestic users will be easier to achieve than for industry. According to the most recent data available, Romania has consumed about 13.5 billion cubic meters natural gas in 2012 [37]. Although in recent years consumption was relatively constant, for 2020/25 this amount is forecasted to increase by 11% [31]. Considering the assumptions and data presented, the amount of hydrogen to be injected into the natural gas transmission pipelines in 2012 can be calculated: 12,470 tons/year (2%); 31,160 tons/year (5%) and 62,390 tons/year (10%), the amounts potentially to be increased at the above mentioned rate.

A number of technical solutions has been proposed, and are now being closely assessed to develop potential future business cases: (1) admixture of hydrogen to the existing natural gas transport grid (2%, 5% or 10%), (2) Power-to-Gas concept, i.e. methanation of electrolytically produced "green hydrogen" with CO_2 from several resources (power plants, biogas plants, other industry and extraction from air) or only lately (3) the conversion of natural gas sub-grids to 100% hydrogen use. Until now, no decision has been taken by the gas industry, which of the options will be selected for which application. Different concepts may coexist and that different options may be preferred. Furthermore, no economically viable business options have been identified for the short-term.

Use of hydrogen in order to balance the electricity supply system is not a new idea, scientists discuss about this, especially considering its role for energy storage and here again to balance renewable electricity. The power sector agrees that hydrogen (or methane, if is discussed about entire power-to-gas concept) storage at large scale will need to be developed to globally contribute to electricity storage, but only, if economic synergies with other hydrogen consuming industry sectors can be identified. If the hydrogen plays a role for energy balance the curtailment is a non-option.

The forecast about market and system integration of renewable energies between 2030 and 2050, assumes that the electricity grid becomes a bottleneck. Hydrogen storage could then both contribute to level out the renewable electricity surplus at supply side and electricity shortages at user side, as well as help to solve local grid congestion challenges. Potential business cases would then be driven by "volatility" vs. "spark spread" (no energy transformation).

For the case of the Romanian electricity production from renewable energy hydrogen is considered for a scenario where renewable, specifically wind energy, will reach an installed power of 4000 MW by 2025, or 6000 MW by 2050, respectively, the number of full loads hours being 2350 per year. From this a portion of 5–10% is considered to be in excess, it is indicated to avoid the term of curtailment. The hydrogen produced from excess of renewable electricity must be consumed for power needs or fuel cell applications, both mobile and stationary. From calculations that take into account the amount of electrical power, electrolysers efficiency and lower heating values, it results that production will be between 9600 H_2 tons/year and 19,200 tons/year by 2025, and 14,400 H_2 tons/year and 28,800 H_2 tons/year by 2050, respectively.

Electricity production from hydrogen will probably take place at sites with strong grid connections (e.g. sites of today existing plants) or at least at sites with transformer station (electrical substations) of TSO (220–400 kV). All the places mentioned are in the vicinity of an electricity distribution network with transformer station (110 kV). Around of all four cavern locations there are no important power plant

Table 5 – Distances between selected sites and transformer stations (electrical substations) of TSO.

Site	Station: 220–400 kV	Station: 110 kV
Ocna Mures	50 km	<10 km
	25 km	
Targu Ocna	30 km	<10 km
	25 km	
Ocnele Mari	10 km	<10 km
Cacica	30 km	<10 km

capacities, the authors do agree that the distance to the transformer station of TSO (220–400 kV) and the distribution stations (110 kV) will play an important role in the future development of hydrogen-to-power infrastructure, (see Table 5).

Identification of sites for storing hydrogen into caverns was done considering the salt-caverns infrastructure. Fig. 2 compares the estimates of hydrogen demand as described in above paragraphs. It has to be noted that those numbers only give a rough estimate of the possible future hydrogen demand in Romania.

The geological conditions are assumed to remain constant for this period and also, the feasibility criteria are only relevant for the time of construction which would be between 2020 and 2025. The possible contamination and leakage are well described in literature (see Ref. [1]), special attention must be paid to proof of tightness for H_2 (synthetic seals, interface salt-cementation-steel) and adaptation of steel components (proof of resistance against hydrogen embrittlement, use of steel suitable for hydrogen).

According with the HyUnder project criteria, which refer to the evaluation of locations like: good geological conditions, cavern field in conservation; were identified possible areas which now are used for brine consumption by local industry. These criteria could be limited even if this industry is very strong in that specific region, because long-term contracts (up to 10 years). This leads to a saturated market which does not need additional brine.

Prototypical caverns are operated at pressures between 6 MPa and 180 MPa. Throughout HyUnder project, a cavern size of 500,000 m^3 has been considered as reference. There is need to respect the cushion gas which remains in the caverns at minimum pressure, to keep the cavern stable. The gas remained is part of capital expenditure and cannot be considered and used as working gas. The working gas is difference between the gas content at maximum and minimum pressure. Taking into consideration the physical and chemical parameters (volume, density, compressibility factor, etc.), this means 5000 tons H_2.

Discussions

The large scale hydrogen storage facilities are obviously dependent on the hydrogen infrastructure build-up in Romania. National, multinational or European hydrogen infrastructures imply both large and small scale hydrogen storage. The best options for the large quantities storage of hydrogen over long periods of time are salt caverns.

Excluding industry, characterized by already existing good correlations between hydrogen supply and demand with an existing hydrogen infrastructure including storage capabilities, the other sectors as indicated in above paragraphs and Fig. 2, have shown a principal but general interest for an analysis of the large scale hydrogen storage in salt caverns. The chemical industry, both refineries and ammonia production, can become interested to participate in this market if cheap surplus quantities should become available.

Hydrogen stationary applications and fuel cell technologies in the energy sector, both electricity and natural gas, could solve the problem of intermittent transmission by seasonal energy storage with hydrogen energy at large scale. The need of energy storage is an actual problem for several markets. In the short and medium term, Romania's energy strategy foresees to provide an increased gas storage capacity of up to 50%, an increasing oil storage capacity to fulfill 67.5 days of annual consumption (2011 reference year) and the construction of a 1000 MW new pumped hydro storage plant [38]. These are good reasons to appreciate the potential of hydrogen underground storage in the energy sector in Romania.

Ranging on par with natural gas it is useful to note that storage should not be a purpose itself. The storage represents only a part of the total costs of the hydrogen value chain. For one mature market, the storage represents around 5% of the total natural gas price paid by residential clients [39]. At the incipient stage, the main roles of hydrogen storage can be considered similar as those for natural gas storage: security of supply, system flexibility, production and transmission optimization, infrastructure sizing, market development or arbitrage.

Hydrogen is just one solution; therefore the suggested approach of a country wide large scale hydrogen energy delivery and storage system needs more detailed analysis. There are not all instruments in place to fully understand the role of energy storage in general and hydrogen underground storage in particular.

Most promising utilization of hydrogen and fuel cell technology is as transport fuel for mobile applications. Hydrogen fuel cell electric vehicles (FCEV) offer the possibility to

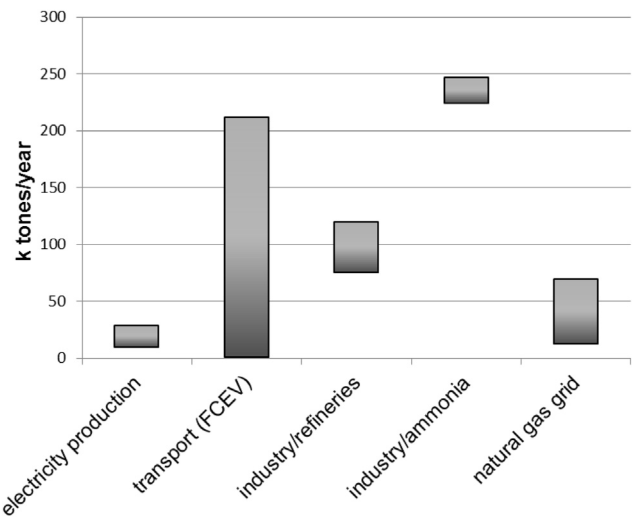

Fig. 2 – Potential H_2 demand bandwidth in Romania.

simultaneously respond to all major energy policy objectives in the transport sector, i.e. CO_2 emissions reduction, energy security and reduction of local air pollution and noise. This sector is promising but it is more difficult to create the required premises in order to calculate the hydrogen storage needs. If benchmarking with the consumption of mineral oil in Romania it can be stated that the hydrogen storage can reach 20% of its annual consumption. It is difficult to estimate how much of these percentages would need to be stored in large underground salt caverns, small storage reservoirs or how much of its volume would be kept in the volumes of the hydrogen distribution and transmission infrastructure.

In the short and medium term the costs of renewable hydrogen, produced by water electrolysis, appears to be far more expensive than hydrogen produced by steam methane reforming. One solution is to store and use hydrogen as energy carrier which does not necessarily mean to produce continuously [40,41].

Conclusions

Four potential locations for hydrogen underground storage in salt caverns in Romania have been identified: Ocna Mures, Targu Ocna, Ocnele Mari and Cacica. The analysis was conducted according with HyUnder project's criteria, which refer to the evaluation of a location set, such as: good geological conditions, cavern field in conservation. The driver for potential utilization of hydrogen underground storage in Romania is the steep gradient of introducing renewable electricity and the lead times foreseen for the cavern development of underground storage of hydrogen at large scale. Also, to identify economic synergies between the other sectors such as mobility, chemical industry and the natural gas sector will need to be investigated by tapping their individual know-how and existing infrastructures for reducing infrastructure costs.

The energy sector, natural gas and electricity as well as the salt industry can all have an important role in hydrogen storage. But most importantly, opportunities are arising due to the need to switch from an outdated industrial infrastructure to a new one. The transport sector is rather more interest in the development of a hydrogen refueling infrastructure than in one for hydrogen underground storage at large scale. Romania is a country with relatively good opportunities to make the transition from the dependence on fossil fuels to an energy system based on renewable energy sources and hydrogen as a new storable energy carrier. Hydrogen underground storage represents only a fraction of the total costs of the hydrogen value chain. The main components of hydrogen large scale underground storage must be: security of supply, system flexibility, production and transmission optimization, infrastructure sizing, market development and arbitrage.

An important step in preparing hydrogen underground storage implementation is to identify the potential stakeholders and to define a network able to serve energy optimization purposes.

The aforesaid can be considered a brief vision of what is pursued by those who believe in a wider and universal role of hydrogen as energy carrier and storage medium in the energy system.

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REFERENCES

[1] Lord A. Overview of geologic storage of natural gas with an emphasis on assessing the feasibility of storing hydrogen. Sandia National Laboratories; 2009. Report no. SAND2009–5878. Contract no.: DE-AC04-94AL85000. Sponsored by the Department of Energy.

[2] Waiters AB. Technical and environmental aspects of underground hydrogen storage. In: Proc. 1st world hydrogen energy conf., Miami Beach, Florida; 1976.

[3] Carden P, Paterson L. Physical, chemical and energy aspects of underground hydrogen storage. Int J Hydrogen Energy 1979;4:559–69.

[4] Foh S, Novil M, Rockar E, Randolph P. Underground hydrogen storage, final report. Chicago: Institute of Gas Technology; 1979. Issued as BNL 51275.

[5] Taylor B, Alderson A, Kalyanam M, Lyle B, Phillips A. Technical and economic assessment of methods for the storage of large quantities of hydrogen. Int J Hydrogen Energy 1986;11(1):5–22.

[6] Lindblom UE. A conceptual design for compressed hydrogen storage in mined caverns. Int J Hydrogen Energy 1985;10(10):667–75.

[7] Schaber C, Mazza P, Hammerschlag R. Utility-scale storage of renewable energy. Electr J 2004;17(6):21–9.

[8] Stone H, Veldhuis I, Richardson N. An investigation into large-scale hydrogen storage in the UK. In: Proceedings international hydrogen energy congress and exhibition IHEC; Istanbul; Turkey; 13–15 July 2005.

[9] Lord A, Kobos P, Borns D. Geological storage of hydrogen. Sandia National Laboratories; 2009 May. Report no. SAND2009–1840C. Contract no.: DE-AC04-94AL85000. Sponsored by the Department of Energy.

[10] Sørensen B. Underground hydrogen storage in geological formations, and comparison with other storage solutions. HYdrogen POwer THeoretical and engineering solutions – international symposium, March 27–30, 2007; Merida, Yucatan, Mexico.

[11] Sørensen B. An energy storage tale. Renew Energy Focus; 2009 May/June:26–7.

[12] Crotogino F, Donadei S, Bunger U, Landinger H. Large-scale hydrogen underground storage for securing future energy supplies [CD-ROM]. In: 18th world hydrogen energy conference; 2010 May 16–21; Essen, Germany. EnergieAgentur. NRW; 2010.

[13] Basniev K, Omelchenko R, Adzynova F. Underground hydrogen storage problems in Russia [CD-ROM]. In: 18th world hydrogen energy conference; 2010 May 16–21; Essen, Germany. EnergieAgentur. NRW; 2010.

[14] Roads2HyCom Hydrogen and Fuel Cell Wiki [Internet]. Large hydrogen underground storage [updated 2008 March 26; cited 2014 March 10]. Available from: http://www.ika.rwth-aachen.de.

[15] Kruck O, Crotogino F, Prelicz R, Rudolph T. Overview on all known underground storage technologies for hydrogen. HyUnder; 2013 August. Deliverable No. 3.1. Grant agreement no.: 303417. Sponsored by FCH JU; EU.
[16] Murray ML, Seymour EH, Pimenta R. Towards a hydrogen economy in Portugal. Int J Hydrogen Energy 2007;32:3223–9; Leben J, Hocevar D. Correlation between national development indicators and the implementation of a hydrogen economy in Slovenia. Int J Hydrogen Energy 2012;37:5468–80.
[17] Maclaurin D, Slater S. Hydrogen and fuel cells – a handbook for communities, vol. A. UK: Element Energy Ltd.; 2007. Available online at: http://www.roads2hy.com [accessed 10.04.13].
[18] Wenisch A, Pladerer C. Energy situation and alternatives in Romania. Vienna, Austria: Austrian Institute for Applied Ecology; 2003.
[19] Transelectrica, Evolution of the net generating capacity in the period 2013–2015. Available online at: www.transelectrica.ro [accessed 01.03.14].
[20] Maisonnier G, Perrin J, Steinberger-Wilckens R. PLANET GbR. European hydrogen infrastucture atlas and industrial excess hydrogen analysis, part II industrial surplus hydrogen, markets and production. Roads2HyCom; 2007 March. DELIVERABLE 2.1 and 2.1a. Document Number: R2H2006PU.1.
[21] Stygar M, Brylewski T. Towards a hydrogen economy in Poland. Int J Hydrogen Energy 2013;38:1–9.
[22] Breya J, Brey R, Carazo AF, Contreras I, Hernández-Díaz AG, Castro A. Planning the transition to a hydrogen economy in Spain. Int J Hydrogen Energy 2007;32:1339–46.
[23] Breya J, Brey R, Carazo AF, Contreras I, Hernández-Díaz AG, Castro A. Designing a gradual transition to a hydrogen economy in Spain. J Power Sources 2006;32:1231–40.
[24] Bockris JM. The hydrogen economy: its history. Int J Hydrogen Energy 2013;38:2579–88.
[25] Iordache I, Gheorghe AV, Iordache M. Towards a hydrogen economy in Romania: statistics, technical and scientific general aspects. Int J Hydrogen Energy 2013;38:12231–40.
[26] Marban G, Valdes-Solis T. Towards the hydrogen economy? Int J Hydrogen Energy 2007;32:1625–37.
[27] Goswami N, Kar S, Bindal RC, Tewari PK. A review of thermochemical cycles for hydrogen production: analysis of potential of membrane technology in I-S, UT-3 and CuCl cycles. Int J Nucl Hydrog Prod Appl 2013;2(4):282–316.
[28] EVUE project [Internet]. Electric vehicles in urban Europe; final report. [cited 2014 March 10]. Available from: http://urbact.eu/fileadmin/Projects/EVUE/.
[29] FCH JU, NOW GmbH. A portfolio of power-trains for Europe: a fact-based analysis. McKinsey & Company; 2011.
[30] Ministerul Afacerilor Interne. Directia regim permise de conducere si inmatriculare a vehiculelor (Romania, Ministry of Internal Affairs, Directorate for driving licenses and vehicle registration) [cited 2014 March 10]. Available from: http://www.drpciv.ro/; 2013.
[31] Comisia Nationala de Prognoza (National Commission of Prognosis). Prognosis of energy balance 2012–2020; 2012.
[32] EUROPIA [Internet]. Annual report [cited 2014 March 10]. Available from: www.europia.com; 2012.
[33] Berssan L, Collodi G, Ruggeri F. Hydrogen generation for modern refineries. Roster Wheeler; 2010.
[34] U.S. Geological Survey. Mineral commodity summaries 2013. Reston; Virginia: U.S. Geological Survey; 2013.
[35] Fertilizer Europe [Internet]. Forecast of food, farming and fertilizer use in the European Union 2012-2022 [citated 2014 March 10]. Available from: www.fertilizerseurope.com.
[36] Eurogas [Internet]. The European Union of the Natural Gas Industry, Eurogas statistical report [cited 2014 March 10]. Available from: www.eurogas.org.
[37] BP Statistical Review of World Energy [Internet]. BP statistical review world energy [cited 2014 March 10]. Available from: www.bp.com/statisticalreview; 2013.
[38] Sandulescu A. The energy sector in Romania, present and future. In: US civil nuclear industry program in Romania. Bucharest; November 2; 2011.
[39] Sulmont F. Natural gas storage: market outlook and business models. Workshop: HyUnder European case studies. Paris; 2014.
[40] Moton J, James B, Colella W. Design for manufacturing and assembly (DFMA) analysis of electrochemical hydrogen compression (EHC) systems. In: Proceedings of EFC2013, fifth European fuel cell technology & applications conference – Piero Lunghi conference; Published by ENEA; 2013. pp. 297–8.
[41] Johnson L, inventor; Johnson Electro Mechanical Systems LLC, assignee. Electrochemical convention system. United States patent US 6709778B2; 2004 Mar. 23.