INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–17

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Relevance and costs of large scale underground hydrogen storage in France

Alain Le Duigou [a,*], Anne-Gaëlle Bader [b], Jean-Christophe Lanoix [c], Lionel Nadau [d]

[a] CEA, France
[b] BRGM, France
[c] Hinicio, Belgium
[d] Engie, France

ARTICLE INFO

Article history:
Received 19 April 2017
Received in revised form
29 June 2017
Accepted 30 June 2017
Available online xxx

Keywords:
Hydrogen
Electrolysis
Storage
Grid
Wind
Mobility
Economy

ABSTRACT

The study analyzes the techno-economic feasibility and business case of large-scale hydrogen underground storage in France. Potential regions for locating the storage cavity were assessed, as well as the anticipated hydrogen demand and renewable energy developments. The business case of salt caverns storage facility has been assessed both in 2025 and 2050, looking at several demand sectors, including mobility (FCEVs), hydrogen-consuming industries and what is defined as "Power-to-Gas". The hourly operation of the cavern has been modeled. The electricity supply is restricted to wind and grid electricity only.

The mobility market is clearly the key driver, both in quantity and economic terms, with an easier to achieve target cost (€4/kgH2, ex-storage). High utilization rates of electrolysers are necessary to reach profitability. A need for massive storage begins for a renewable penetration rate of 50%. The hydrogen costs varies from €4.5/kg to €6.6/kg H2, and the underground mass storage cost remains always under 5% of the overall costs.

Introduction

Recently, CEA, CNRS and IFP Energies nouvelles have created the Alliance Nationale de Coordination de la Recherche pour l'Energie (ANCRE, or French National Alliance for Energy Research Coordination).[1] The Alliance carried out a report which reported on three possible scenarios of evolution of the French energy system in 2050, aiming to achieve the "factor 4" (division by at least 4 Gas Emissions, or GHG, energy-related compared to the year 1990).

The ANCRE scenarios plan ca. 40–45% renewable electricity (hydro, wind, solar) production on a yearly basis. Increasing production of fluctuating renewable energy intensifies the need for electricity storage to ensure grid reliability and flexibility. While short term energy storage can be met by small decentralized storage systems, mid to long term electricity storage technologies are still lagging behind. Using hydrogen as a mean to store energy in the long run may in the future help address the challenge of grid balancing when large quantities of fluctuating renewable electricity are introduced

* Corresponding author.
E-mail address: alain.le-duigou@cea.fr (A. Le Duigou).
[1] http://www.allianceenergie.fr/en/index.aspx.
http://dx.doi.org/10.1016/j.ijhydene.2017.06.239

Nomenclature

HOMER	Hybrid Optimization of Multiple Energy Resources (http://www.HOMERenergy.com/)
NREL	National Renewable Energy Laboratory
CHP	Combined Heat and Power
PV	Photovoltaics
FCEV	Fuel Cell Electric Vehicle
T&D	Transport and Distribution
Hythane®	Mixture of 20% (molar) hydrogen in natural gas
CAES	Compressed Air Energy Storage
NPC	Net Present Cost
COH	Cost of Hydrogen
CAPEX	CAPital EXpenditure (investment)
OPEX	OPerating EXpenditures
O&M	Operating and Maintenance
R&D	Research & Development

in the energy mix. Although large scale underground gas storage is in general a relatively mature solution from an economic and technical perspective, hydrogen underground storage before becoming a potentially attractive solution still needs to be evaluated thoroughly from a technical, economic and societal standpoint.

A European project, named HyUnder, started in summer 2012 for 24 months, and aimed to assess the potential, actors and business models of large scale underground hydrogen storage in Europe. Large-scale storage of hydrogen in underground salt caverns is one of the options at our disposal to provide flexibility to the power system. It could also be a cornerstone for the infrastructure necessary to supply green hydrogen to a range of sectors and applications, including Fuel Cell Vehicles and the natural gas grid (so-called “Power-to-Gas”).

Analysis of the literature

In most articles showing that electricity prices and electrolytic operations are key factors influencing the competitiveness of hydrogen production processes, the objective is to reduce the cost of hydrogen production via electrolysis by proposing different strategies. Among those strategies, hydrogen storage is often cited, mainly at small scales by using more or less high pressure bottles. Hydrogen is far to be a real gas, and its high pressures behavior is very difficult to modeling [1]. Hydrogen storage remains expensive, as showed by Ref. [2]: their study has shown that the cost of producing hydrogen from wind-generated electricity varied widely depending on the configurations tested, and that the costs could differ significantly depending on the demand profiles concerned. In the case of supplying a filling station, the variability of demand was another factor to add to the variability of the resource, making it necessary to include expensive hydrogen storage facilities in the system and then leading to costs up to ca. 20 h/kg, the storage accounting for ca. 50% of the cost. Aguado et al. [3] showed too that if wind energy electrolysis associated with hydrogen storage is a good solution to lower grid management issues, nevertheless it does not compensate for the additional investment in the hydrogen storage system.

Botterud et al. [4] assessed the profitability of various nuclear hydrogen production technologies under uncertainty in hydrogen and electricity prices. They used Monte Carlo simulation to describe those uncertainties, and the real-options method to assess the investor's profits from investing in a nuclear hydrogen plant capable of switching between electricity and hydrogen. Product flexibility increases the expected profits and lowers the overall financial risk. Hydrogen storage should further improve the system's profitability. Taljan et al. [5] have studied the feasibility of hydrogen storage for a mixed wind–nuclear power plant with the option of direct hydrogen selling and considering the utilization of residual heat and oxygen. The system is economically feasible with high rates of returns, and profitability is considerably higher when heat and oxygen are sold too. In this case, the hydrogen system is mainly used at a profit to produce hydrogen for use in transportation and industrial markets, rather than for electricity storage. Sanchez and Gonzalez [6] improved grid stability by means of hydrogen production. The system is composed of a wind farm, a biomass gasification plant, a photovoltaic plant, a battery bank, a hydrogen production system with high pressure storage, and a fuel cell to produce electrical energy from stored hydrogen (HiDRENER project). Hydrogen production and storage is helpful for this operation, even if controlling the entire system is very complex.

Large scale use of hydrogen may require massive storage comparable to natural gas to balance supply and demand [7,8]. This is specifically relevant for the production of renewable hydrogen from intermittent sources such as wind energy [9]. Storage remains essential to connect large scale hydrogen continuous production with seasonal demands. The mass storage will interact with the hydrogen grid similar to the buffering capabilities in the current natural gas grid, but technical requirements and strategy may strongly differ: natural gas storage in France responds to both winter/summer stationary use fluctuations and strategic choices, whereas H2 mass storage would be linked to monthly demand changes, related for instance to the variations in automotive uses.

Tietze and Stolten [10] analyzed the behavior of hydrogen and methane with respect to typical thermodynamic storage processes in order to allow an assessment of a future hydrogen supply system relative to the existing one for natural gas, in a salt cavern. They showed that the work required to compress hydrogen is higher than the corresponding one of methane. In any case, ideal gas assumption leads to big errors, but the behavior of both gases shows only minor divergences. The pressure increase during injection is higher for hydrogen than for methane. To summarize, from the point of view of theoretical calculations, no obstacles exist in transporting and storing hydrogen in a supply infrastructure similar to the existing one for natural gas, and therefore the experience gained on natural gas can be very profitable for the massive underground storage of hydrogen, at least in saline cavities.

Large scale gas storage, and consequently hydrogen storage, is associated with geological underground storage. Underground hydrogen storage exists since decades: BOC,