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Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition

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ABSTRACT

The Plan-DelyKaD project focused on an in-depth comparison of relevant electrolysis technologies, identified criteria for and selected most relevant salt cavern sites in Germany, studied business case potentials for applying hydrogen taken from storage to different end-users and engaged in identifying the future role of hydrogen from large scale storage in the German energy system. The focus of this paper is on the latter three topics above. The bottom-up investigation of most suitable salt cavern sites was used as input for a model-based analysis of microeconomic and macroeconomic aspects. The results identify dimensions and locations of possible hydrogen storages mostly in Northern Germany with ample potential to support the integration of fluctuating renewable electricity into the German power system. The microeconomic analysis demonstrates that the most promising early business case for hydrogen energy from large scale storage is its application as a fuel for the mobility sector. From a system perspective the analysis reveals that an optimized implementation of hydrogen generation via electrolysis and storage in salt caverns will have a positive impact on the power system in terms of reduced curtailments of wind power plants and lower residual peak loads.

Introduction

The future role of hydrogen in the energy system

Since the early demonstration projects aiming at an introduction of hydrogen as a universal energy carrier in the 70s–80s (e.g. the HySolar project [1], the Solar Hydrogen Bavaria project [2] and the Euro-Quebec Hydro-Hydrogen Pilot Project [3]) the key role of hydrogen had been reduced to becoming a fuel for mobility, and here specifically for passenger cars (e.g. the Transport Energy Strategy in Germany [4]). The potential contribution of hydrogen energy as an energy carrier system has recently gained fresh attention both from policymakers and industry in the wake of the

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"Energiewende" discussions in Germany intensifying since 2011 and the need to replace fossil energy by fluctuating renewable energy (e.g. Ref. [5]).

One element of this strategy is to convert electricity primarily in periods with more wind and solar generation capacities available than momentarily required to store it for periods when power demand surpasses the renewable generation capacity. The focus of the potential contribution here is on the energy storage for weeks or even months. Underground salt caverns have been identified as a possible core technology for large scale hydrogen storage in some regions and it could be shown in a European study [6] that among other regions Northern Germany is the one with largest salt cavern storage potentials. Fortunately, this regional focus coincides well with the availability of ample renewable electricity generated from wind energy on- and offshore the northern German coastline.

As a consequence, several pilot projects had been proposed as early showcases for the Power-to-Gas, and more specifically Power-to-Hydrogen (PtH_2) concept, the power contributed from wind energy in this case and the gas being hydrogen for storage and later use. To better understand technical and economic opportunities and constraints of this concept the German Federal Ministry for Economic Affairs and Energy (BMWi) had suggested a study on the core elements of the PtH_2 technology, i.e. the hydrogen production by electrolysis and the storage of hydrogen in salt caverns. Issues of specific relevance in this context were the selection of the most suitable electrolysis technology, i.e. proton exchange membrane (PEM) or alkaline electrolysis, the most suitable German salt cavern locations and the corresponding economics from the business and system perspective for the installation of large scale salt cavern based PtH_2 plants. The study Plan-DelyKaD was finally launched in 2012, jointly carried out by the project partnership of DLR (German Aerospace Center), FhG-ISE (Fraunhofer Institute for Solar Energy Systems), KBB UT (KBB Underground Technologies GmbH) and LBST (Ludwig-Bölkow-Systemtechnik GmbH), the final report of which was presented to the public in February 2015 [7].

Objectives and methodology applied by the Plan-DelyKaD research project

The main objective of this contribution is to integrate substantiated and up-to-date characterizations of hydrogen generation by electrolysis and storage in salt caverns into economic analyses from two different perspectives. The first perspective is a microeconomic one represented by a prototypical operator delivering hydrogen to four different markets, namely transport, industry, natural gas and power generation (i.e. reconversion into electricity). The second perspective is of macroeconomic relevance by analyzing systemic effects of hydrogen generation and storage in a future power system dominated by variable renewable electricity sources (RES). The model-based analyses are done based on current state of knowledge about electrolysis according to [7] and results of a spatial analysis of geologic storage potentials presented in this contribution. The modelling focuses on hydrogen generation and storage costs as well as on power system costs. The latter is determined by residual peak loads and losses due to power storage and RES surpluses. Uncertainties of model-based calculations are addressed by sensitivity analyses and by comparing different scenario variants. The overall objective is to find answers to questions about the profitability of investments in hydrogen infrastructure and associated challenges and benefits for the future German power system.

The in-depth analysis of spatial distribution and storage capacities of salt caverns in Germany is an essential input to the model-based systems analyses. A detailed site assessment was carried out applying defined geologic and geotechnical criteria and taking into account historic experiences from other countries and already existing caverns mostly located in the northern part of Germany. This leads to an estimation of storage potentials in spatial resolution (See Potential for hydrogen underground storage). Future business cases are analyzed simulating the operation of a single hydrogen plant with future energy prices and techno-economic parameters. Hydrogen revenues are estimated for different markets based on today's situation and plausible future developments. Different technical and economic framework conditions and their sensitivities on cost factors are evaluated. The variable influence of the power system and resulting electricity price time series are taken into account via hourly simulation of hydrogen production using a dedicated optimization model (see section Microeconomic analysis of hydrogen generation and storage costs in different markets for model description and section Microeconomics of hydrogen generation and storage for the results of the microeconomic analysis).

The analysis of systemic effects is done by applying a power system model with consistent parametrization. It is based on scenarios describing the long-term transition of the energy system according to the political targets set in Germany (see Ref. [8]). The temporal but also spatial differentiation of power demand and supply are essential aspects for analyzing an optimized expansion and operation of the power system. A hydrogen supply using central storage in salt caverns is therefore compared to decentralized on-site hydrogen generation and storage at fueling stations. The results are calculated for two different long-term scenarios with hydrogen use for mobility and electricity generation (reconversion), respectively (see section Model-based macroeconomic analysis of systemic effects of hydrogen generation and storage on the future power supply system for model description and section Interrelations between hydrogen generation and storage infrastructure and the power system for the results of the macroeconomic analysis). The discussion of the results leads to comprehensive conclusions (See Conclusions and outlook).

Potential for hydrogen underground storage

Salt caverns are man-made, often cylindrically-shaped, cavities in thick underground salt deposits which are constructed from the surface by the controlled injection of water down a well drilled into the salt rock – a technology called solution mining. Depending on the specifications and the technical feasibility, they can be constructed at depths of down to 2000 m, have geometric volumes of up to 1,000,000 m^3, typical heights of 300–500 m, and diameters of