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Seasonal storage and alternative carriers: A flexible hydrogen supply chain model

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HIGHLIGHTS

- Techno-economic model of future hydrogen supply chains.
- Implementation of liquid organic hydrogen carriers into a hydrogen mobility analysis.
- Consideration of large-scale seasonal storage for fluctuating renewable hydrogen production.
- Implementation of different technologies for hydrogen storage and transportation.

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ABSTRACT

A viable hydrogen infrastructure is one of the main challenges for fuel cells in mobile applications. Several studies have investigated the most cost-efficient hydrogen supply chain structure, with a focus on hydrogen transportation. However, supply chain models based on hydrogen produced by electrolysis require additional seasonal hydrogen storage capacity to close the gap between fluctuation in renewable generation from surplus electricity and fuelling station demand. To address this issue, we developed a model that draws on and extends approaches in the literature with respect to long-term storage. Thus, we analyse Liquid Organic Hydrogen Carriers (LOHC) and show their potential impact on future hydrogen mobility. We demonstrate that LOHC-based pathways are highly promising especially for smaller-scale hydrogen demand and if storage in salt caverns remains uncompetitive, but emit more greenhouse gases (GHG) than other gaseous or hydrogen ones. Liquid hydrogen as a seasonal storage medium offers no advantage compared to LOHC or cavern storage since lower electricity prices for flexible operation cannot balance the investment costs of liquefaction plants. A well-to-wheel analysis indicates that all investigated pathways have less than 30% GHG-emissions compared to conventional fossil fuel pathways within a European framework.

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1. Introduction

The transition to renewable energy is a centrepiece of global environmental policies. The Paris Agreement from November 2015 is intended to reduce net green-house gas (GHG) emissions to zero by the second half of this century [1,2]. The targets set out by the German government foresee a reduction of GHGs in the energy system of 80% by 2050 against 1990 levels [3]. These targets fundamentally depend on the penetration of renewable energy technologies like wind and solar power across all energy sectors. For example, in 2015 the German electricity sector already produced 32.6% renewably [4]. However, with increasing renewable power, the necessity of storage options to counter the effects of the fluctuating nature of wind and solar power correspondingly rises. In 2014, 1581 GWh of renewable power was curtailed due to grid congestion, resulting in compensation payments by the EEG levy[1] of 82 million Euro [4]. To avoid such financial and efficiency-

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[1] The German EEG levy was introduced in the year 2000 with the German Renewable Energy Act (EEG). It supports the penetration of renewable energy in the power sector by setting fixed feed-in remunerations for renewably-generated energy. Furthermore, renewable energy gain unlimited priority feed-in. In case of curtailment of renewable power generation due to grid congestion, the renewable energy plant gets compensation payments for the loss of revenues. The EEG represents the gap between revenues and expenses caused by renewables and is paid by the consumers [61].

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usurious costs, with the share of renewables projected to be 80–100% by 2050, Germany is in need of storage options at the TWh-scale, which can be achieved with Power-to-Gas via water electrolysis [5,6]. Meanwhile, the mobility sector accounts for around 17.7% of total GHG emissions in Germany [4]. In 2015 however, renewables met only 5.3% of the total energy consumption of this sector [7]. Furthermore, the latest figures on air quality in German cities indicate major problems in fulfilling European regulations [8]. Zero emission vehicles like battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) fuelled by renewably-produced hydrogen have the potential to reduce both CO_2 emissions and locally active pollutants at the same time [3,9]. Moreover, hydrogen facilitates the coupling of electricity with the mobility sector: producing hydrogen via electrolysis during periods when high renewable power generation exceeds grid load would offer an emission-free fuel for FCEVs [10–13].

Establishing hydrogen as a fuel for transportation requires a detailed analysis of the entire supply chain. This includes how hydrogen is to be produced, its large-scale storage that takes the seasonal intermittency of renewable power generation[2] into account, its transportation and distribution from a central production plant to fuelling stations as well as the fuelling stations themselves. The optimal tank storage system for on-board storage in FCEVs is generally considered to be a 350 or 700 bar compressed gas vessel [14]. However, the supply chain up until the onboard storage is still a focus of investigation. Numerous studies [14–19] investigate the most cost-efficient supply structure between production and transportation. The "state of the art" hydrogen supply chain thereby mostly relies on pure hydrogen provided as compressed gas or cryogenic liquid [20,21]. Yang and Ogden [22] investigate a method for comparing the different transport possibilities of tube or liquid trailer truck vs. pipeline delivery. They show that each technology has a maximally cost-efficient niche and there is no single perfect solution for the entire system. Elgowainy and Reddi [18] develop an Excel tool for calculating the cost of hydrogen supply while varying different input parameters like FCEV market penetration, refuelling station capacity, transmission mode or production volume for different delivery scenarios. Like Yang and Ogden, they focus on the three main delivery pathways of tube trailer, liquid trailer and pipeline. Although, hydrogen production is not calculated inside either model and is instead assumed to be an input. As such, the influence of hydrogen production on storage demand was not investigated and, considering hydrogen mobility as part of a future renewable energy system and the utilization of electrolysis systems from renewable sources, this influence should not be overlooked. Seasonal storage is identified as a key factor in several studies [10,18], although only consideration of subterranean options, such as salt caverns or depleted oilfields, has been found.

High-pressure storage tanks remain cost-intensive (800 $/kg hydrogen [23]) while the liquefaction of hydrogen is energy-intensive (30% of the LHV of hydrogen [24]). Aside from the compressed and liquid applications, many different storage solutions for hydrogen are possible. Chemisorption – like metal hydrides, chemical hydrides or liquid organic hydrogen carrier (LOHC) – along with physisorption – via carbon nanotubes or metal organic frameworks (MOF) – are the two basic mechanisms for storing hydrogen other than conventional compressed and liquid storage [25]. The 2010 Nexant Report [15] included alternative carrier systems like LOHCs and metal hydrides in its calculations. Thereby, it was determined that "using alternative carriers in a pathway that discharges hydrogen at the fuelling station and supplies compressed hydrogen to vehicles will offer little or no benefit for fuelling station costs" [15]. In contrast, Teichmann [2,26,27] shows that the main benefit of an LOHC system lies in the ease and low cost of storage and transportation.

According to Dagdougui [28], most hydrogen supply chain models focus on mathematical optimization methods to minimize the cost of an explicit case, like Samsatli [29], who models a hydrogen infrastructure for supplying Great Britain's transport sector with hydrogen. Nevertheless, the literature is lacking a modelling approach that enables the easy investigations of upcoming new technologies for hydrogen infrastructure like LOHC or additional chain parts like seasonal storage. Implementing them directly into an optimization approach without checking their potential applicability will diminish the model performance. Therefore, this work investigates the application area of different hydrogen supply chain architectures through a point-to-point analysis based on the methodology of Yang and Ogden drawing on current data and extending the considered technologies. Therefore, it considers the full supply chain from hydrogen production by electrolysis, large-scale storage for the temporal gap between demand and supply, the transportation and the fuelling station facilities necessary to fill a 700 bar compressed gas tank. Furthermore, LOHCs are discussed as an alternative carrier system to investigate their impact on hydrogen mobility. All results shown with this model have a European scope. Applying this model to other regions of the world could significantly change the results. Nevertheless, the elaborated sensitivity analysis of this paper shows the most sensitive input parameters.

2. Hydrogen storage and delivery

2.1. Storage methods

A key challenge for hydrogen mobility is its extremely low density (0.09 kg/m^3), in accordance with its being the lightest element [30,31]. Even with a high specific energy of 33 kWh/kg, energy density remains low at ambient conditions (0.003 kWh/l) compared to conventional fuels such as gasoline (10 kWh/l). Depending on the storage and transportation technology, higher energy densities lead to lower specific costs due to limited volume and weight. Therefore, the energy density of hydrogen requires further adjustments.

Fig. 1 displays the volumetric and gravimetric density ranges of different technologies for hydrogen storage found in literature. Compressed and liquid hydrogen are the current state of the art in hydrogen storage. All alternative hydrogen carriers substances like MOFs, metal hydrides, chemical hydrides or LOHCs were initially investigated for on-board hydrogen storage in a fuel cell vehicle. However, the on-board hydrogen storage system seems to be fixed for the near future at 700 bar [14]. This study focuses on infrastructure for the storage and transportation of hydrogen. While storage systems for mobile storage allow higher capital investments, the use of carrier systems for the supply infrastructure requires a cheap carrier compound with easy handling and a high hydrogen share. Solid carriers like MOFs or metal alloys do not fulfil these requirements. Chemical and metal hydrides still lack regenerable carriers, which are not dismantled during unloading, with scalable loading and unloading reactions, and offering easy transportation of the loaded and unloaded carrier compound. LOHCs are thereby promising candidates for hydrogen infrastructure, since the loaded as well as unloaded carrier exist naturally in a liquid state [2,26,33–35]. From here, each of the storage methodologies implemented in this work are explained in finer detail.

2.1.1. Compressed hydrogen

The most common way to achieve higher hydrogen storage densities is via compression in gaseous form (GH_2). Stationary tube

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[2] In case of Germany, wind power plants produce more energy during the winter than the summer contrary to photovoltaic, which produces more in the summer.

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