Hydrogen Storage for Renewable Energy Integration: A Techno-Economic Comparison with Ammonia as Hydrogen Carrier

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Keywords: Ammonia as Hydrogen carrier, Hydrogen Storage, Renewable Energy Integration, Techno-economic analysis

Abstract

Introduction: The global fight against climate change is tied to the development of contemporary energy policies, which have established ambitious targets to curtail greenhouse gas emissions and facilitate the transition to a sustainable energy system. Renewable energy sources are pivotal to this transition, but their intermittent nature poses significant challenges. In this regard, the development of long-term storage technologies has emerged as a crucial solution. The ability to store excess energy and utilize it at later times is fundamental in managing the fluctuations in renewable generation, thereby reducing the necessity to rely on conventional power plants. Moreover, energy storage has the potential to address not only temporal but also spatial challenges, facilitating the transfer of energy from areas with surplus production to areas with insufficient renewable production due to unfavourable weather conditions. Currently, chemical storage using hydrogen appears to be the most promising solution to meet these requirements. Nevertheless, the technical and economic challenges associated with hydrogen storage and transportation necessitate the exploration of alternative solutions. One promising solution is using ammonia (NH_3) as a hydrogen carrier. The utilization of ammonia as a hydrogen carrier can offer several advantages [1]. Ammonia has a hydrogen content of 17.8% in weight, is very stable at ambient conditions and allows for much less severe storage conditions than compressed hydrogen. Moreover, it possesses a lower flammability and volatility compared to hydrogen, enhancing safety. The infrastructure for handling and transporting ammonia is already well-developed, facilitating its use as an energy carrier on an industrial scale.

Objectives: This study aims to evaluate how hydrogen storage in the form of ammonia could contribute to the development of the hydrogen supply chain. To this end, a comparative analysis is conducted between the direct storage of compressed hydrogen and its conversion to ammonia, followed by ammonia storage and subsequent decomposition to obtain

hydrogen. The analysis is performed across various demand profiles to identify the scenarios in which each system exhibits an economic advantage. Finally, a parametric analysis was conducted, considering the costs associated with transportation. This analysis is aimed to evaluate whether the utilization of ammonia as a hydrogen carrier would confer an additional benefit regarding transportation.

Material and methods: The analysis is conducted using an in-house developed software called Multi Energy System Simulator (MESS) [2]. MESS is a modular, bottom-up, multi-node model that allows the simulation of energy systems with multiple energy carriers, multiple users, and adjustable spatial resolution. The simulations are based on a set of predefined priorities, allowing different control logics to be analysed. The model is capable of simulating, at each timestep, the energy balance of the system under consideration, with accurate performance analysis of the various technologies for which design and off-design models have been developed [3]. Within MESS, a realistic and detailed ammonia synthesis reactor model from green hydrogen was developed ad-hoc for this study, together with an ammonia storage and an ammonia decomposition model. The considered case study consists of the comprehensive modelling of the hydrogen supply chain to assess the feasibility of decarbonization of an electricity demand. The electricity demand is met with priority by Renewable Energy Sources (RES). If RES production exceeds demand, the surplus is supplied to a Proton-Exchange Membrane (PEM) electrolyser to produce green hydrogen, which is then stored and converted back into electricity through a PEM fuel cell when demand exceeds production. In the storage phase, the case of compressed hydrogen storage in tanks is compared with the use of ammonia as a storage carrier. In the latter scenario, the hydrogen is utilized to produce green ammonia in a synthesis reactor. Given the necessity of the reactor to maintain operation for technical reasons, requiring a minimum load of 30%, a hydrogen buffer is employed before the synthesis reactor to ensure its continuous operation. Different control strategies were adopted and analysed for the operation of the reactor. The economic viability of these two scenarios is compared using economic indicators, such as the Levelized Cost of Electricity (LCOE). Three distinct electricity demand profiles were considered in this study: one characterized by the absence of seasonality, one exhibiting heightened energy consumption during the summer months, and one during the winter months. In both configurations, the connection to the electricity grid was not taken into consideration. This decision was made to ensure that the electricity produced would be fully renewable. However, this choice presents significant operational challenges and disadvantages from the perspective of component sizing. Specifically, storage systems must be capable of recovering the seasonal variability of RES production. A meta-heuristic optimization method is implemented to perform the sizing of the system. The algorithm chosen is the adaptive PSO proposed by Zhan et al. [4] and implemented through the Python library Pymoo [5]. A parametric analysis was then conducted to determine the impact of the production plant's location relative to the consumption site on the selection of optimal storage technology. This analysis incorporated transportation cost data from existing literature and examined the variation in costs as the distance between the production and consumption sites changed.

Results: It is observed that the demand profile has a significant impact on the selection of the optimal storage system. In particular, the demand profile with higher consumption in the summer months benefits direct hydrogen storage, while the "winter-intensive" demand profile makes ammonia very competitive and economically advantageous. In the absence of seasonality, direct hydrogen storage is favorable over ammonia if no control strategy is applied to the reactor with an LCOE respectively of 0.319 and 0.346 €/kWh. Conversely, when a control strategy is adopted, maintaining the reactor at minimum operational load when the buffer level exceeds a specified threshold, the LCOE of ammonia-based storage decreases and at a minimum of 0.309 €/kWh with a 70% threshold. The introduction of transportation costs further enhances the competitiveness of ammonia-based storage, given ammonia's lower transportation costs relative to hydrogen.

Conclusions: The utilization of ammonia as a hydrogen storage medium has the potential to accelerate the development of the hydrogen supply chain, particularly in scenarios where there is spatial and temporal decoupling between hydrogen production and utilization. The results of this study appear both generalizable and reproducible across various contexts where the adoption of renewable hydrogen is expected to play a crucial role in meeting increasingly urgent climate targets in the near future.

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