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Model-based techno-economic evaluation of an electricity storage system based on Liquid Organic Hydrogen Carriers

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HIGHLIGHTS

- A system for the use and storage of renewable electricity is simulated.
- Energy is stored in hydrogen using liquid organic hydrogen carriers.
- Simulations are based on experimental data for dibenzyltoluene.
- A self-sufficient energy storage system is technically feasible but not economical.
- Price of renewable energy production shows the strongest influence on profitability.

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ABSTRACT

A techno-economic evaluation and feasibility study of a stationary electricity storage system is conducted for an application in an industrial plant. The analysis is based on a model that includes both technological and economic components. It assumes that electricity is produced through wind turbines and photovoltaic systems. The produced electricity can be stored by conversion to hydrogen through electrolysis and reconversion through thermal energy converters. The system stores the produced hydrogen using Liquid Organic Hydrogen Carriers (LOHC). As carrier material, dibenzyltoluene is selected. The model includes investment costs and calculations to conduct economic analysis. It is used to create economically optimized systems that give realistic cost estimations. Technical and economic data are taken from in-house experiments, quotes from manufacturers and literature. The application is evaluated for the electricity supply to a BMW Group production site located in Germany. Results show that at present, converting excess energy to heat is a more economical option than electricity storage using LOHC. However, if the goal is to provide a majority (>75%) of the needed electricity with on-site renewable energy, an energy storage system becomes economical to use today. Based on assumptions for the year 2030 a completely self-sufficient energy supply system built in 2030 is competitive to the electricity purchase from the grid.

1. Introduction

Today, almost all carbon dioxide emissions come from fossil fuels, which currently still provide for up to 80% of global primary energy demand [1]. Climate change and rising public awareness have prompted many countries to transition to low-carbon energy systems. That often includes the intensified use of renewable energy sources (RES) like wind and solar.

These energy sources are volatile leading to an increasing spatio-temporal decoupling of supply and demand profiles. To ensure supply security and reliability of energy systems with high shares of variable RES, short and long term energy storage at large-scales is vital [2,3]. The only economically feasible and mature technology for large-scale long-term electricity storage available today is pumped hydro storage systems. But these are limited by their geographical requirements. The current pumped hydro storage capacity in Germany is approximately 40 GWh [4]. This is insufficient to meet todays estimations for storage requirement of at least 1000 GWh for German 2050 RES targets [2]. In case of increasing coupling of the power and heat sector, the requirements

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for storage are expected to decrease [5]. But at least in summer, significant storage requirements remain. A potential solution is producing hydrogen as an energy carrier as it is carbon-free and has a very high gravimetric energy density. It can be produced sustainably by electrolysis of water which is abundantly available on earth, and hydrogen can be used efficiently in fuel cells and internal combustion engines with low emissions.

A major challenge in adoption of hydrogen as carrier for (long-term and large-scale) energy storage is lack of economical, efficient and safe storage, as well as delivery infrastructure. In commercial technologies for local utilization, hydrogen is either stored in a pressurized gaseous state up to 700 bar or in a liquid state at temperatures below −253 °C. Both of these storage concepts are technologically complex, safety-critical and expensive for establishing a large-scale distribution infrastructure. A promising alternative is the chemical storage of hydrogen using Liquid Organic Hydrogen Carriers (LOHC). LOHC allows safe and lossless longterm storage of hydrogen with high energy density for long periods of time. Chemically, LOHC are hydrocarbons which can switch between hydrogen-rich and hydrogen-lean states by hydrogenation and dehydrogenation processes, which is accompanied by heat exchange. Fig. 1 shows the concept of an electrical energy supply system based on LOHC. During overproduction the hydrogen is produced in the electrolyser and stored in the LOHC-system. When the demand exceeds the RE-production the hydrogen is released in the dehydrogenation unit and reconverted into electricity to meet the demand.

Fig. 2 shows these processes for dibenzyltoluene (DBT) which is the LOHC considered in this paper. The exothermic hydrogenation of DBT releases the reaction enthalpy. During the process of the dehydrogenation the same amount of heat is required to keep the reaction running and to release the hydrogen.

Most LOHC are liquid at ambient conditions and have physical properties similar to diesel; hence, they are easy to handle, safe and can use the existing diesel distribution infrastructure. Consequently, LOHC could ease the transition to a hydrogen-based energy system.

1.1. Literature review

In times of decreasing investment costs for RES, the usage of RES for the supply of industrial sites seems to be a viable option [10]. Firstly, it can help to reduce the operational costs depending on the grid electricity prices. Secondly, it reduces the dependence on market developments and thirdly, it also helps to achieve sustainability goals. Due to the intermittency of RES like wind and solar, the supply often does not match the demand for electricity. A possible solution is to use an appropriate storage system. In the last years, storage systems based on hydrogen have received more attention. Especially for stand-alone systems on islands and remote areas, the combination of RES and hydrogen storage systems has widely been analyzed [11]. The studies can be grouped according to the use of energy sources: PV [12,13], wind [14–17] or hybrid systems [18,19,12] and storage options: only hydrogen [16,17] or hybrid storage systems [12,13,20,21]. Some concentrate more on the control system aspect [21–23], while some have an explicit regional focus [19,24–26].

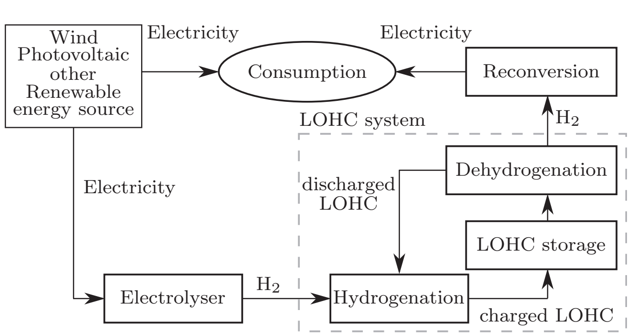

Fig. 1. Concept of electricity storage using LOHC. Concept by [6], own illustration.

Zoulias and Lymberopoulos [27] compared an existing hybrid stand-alone power system and an optimized hydrogen-based system. They found that the use of hydrogen technologies is technically feasible, but still not economically viable. Carapellucci et al. [28] developed a model to evaluate the techno-economic performance of RES combined with a hydrogen storage system as supply of island systems with electricity and optional hydrogen demand. They analyzed different configurations and found that the configuration with a micro-hydro turbine has the lowest costs of electricity and hydrogen compared to systems with PV and wind power. Kalinci et al. [29] studied a hybrid RES system including hydrogen production and storage options (pressurized gas tank) for an island in Turkey. Based on the analysis with an optimization tool, they report that the system is technically feasible but is still an expensive method. Kroniger and Madlener [30] evaluated the combination of four different business models for an hydrogen storage system: increase of the utilization rate of a wind park in the presence of grid overload, achievement of profits by arbitrage transactions, provision of system services (minute reserve) and direct marketing of hydrogen. They also found that the option as storage for electricity is not profitable under the prevailing boundary conditions in Germany. Chauhan and Saini [31] present a comprehensive review on RES with different storage options including different configurations, sizing methodologies and control for energy flow management.

Most of these studies analyzed energy systems including conventional hydrogen storage technologies and further, not for applications on industrial sites.

In the literature, the most researched LOHC is N-Ethylcarbazole (NEC). While there is plenty of literature about kinetics and thermodynamics of hydrogenation and dehydrogenation reactions, literature with application-specific evaluation is relatively scarce. First techno-economic evaluations of an LOHC-system were published in [32–34]. Scherer et al. [32] introduced the concept for seasonal electrical energy storage based on a LOHC-system. The LOHC-system is based on Methylcyclohexane and Toluene and used for the seasonal storage of surplus summer hydro-electricity for usage in winter. In [34] the electricity storage based again on Methylcyclohexane and Toluene is compared to other energy storage technologies and also to the construction of new hydro-power plants. Results reveal that the LOHC-system showed similar or superior performance to other energy storage technologies and economical competitiveness with new hydro-power plants. In [33] a more detailed economic evaluation of the above concepts is made, which features different cases of economic parameters and also different regulations regarding the electricity production on the location of the storage plant. This study differs from the work in [32–34] especially through the evaluation of a coupling with fluctuating electricity production through photovoltaics and wind turbines and the newly discovered LOHC, dibenzyltoluene.

Patents were filed on the use of LOHC in stationary systems [35–40]. Several of these describe the use of LOHC for direct use of hydrogen, i.e. for hydrogen fueling stations [36,37]. The use in energy storage systems is described in [38–40]. Specifically for the energy supply of buildings, the patent [40] was filed. Detailed reactor design for stationary or mobile applications are described in [41–44].

Gahleitner [45] mentions LOHC as a possible energy carrier for gas turbines, fuel cells or transport applications. Teichmann, Arlt and Wasserscheid [46] make a detailed cost and energy consump-