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Exergy and cost analyses of hydrogen-based energy storage pathways for residual load management

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ABSTRACT

Hydrogen is considered to become a main energy vector in renewable energy systems to store large amounts of intermittent wind and solar power.

In this work exergy efficiency and cost analyses are conducted to compare pathways of hydrogen generation (PEM, alkaline or solid oxide electrolysis), storage (compression, liquefaction or methanation), transportation (trailer or pipeline) and utilization (PEMFC, SOFC or combined cycle gas turbine). All processes were simulated with respect to their full and part-load efficiencies and resulting costs. Furthermore, load profiles were estimated to simulate a whole year of operation at varying loads.

The results show power-to-power exergy efficiencies varying between about 17 and 38%. The main losses occur at utilization and generation. Methanation features both lower efficiency and higher costs than compressed hydrogen pathways. While gas turbines show very high efficiency at full load when considering a load following operation they drop significantly while fuel cells can maintain their efficiency.

Lower costs are commonly reached at higher overall efficiencies. Installation costs are identified as predominant because of the low amount of full-load hours. An increase of these e.g. by accounting for an electrolysis base-load to provide hydrogen for vehicles shows significant decreases in costs per stored energy.

Introduction

The goal of a sustainable energy infrastructure in Germany requires the dominant sources of electric power to be hydro, biomass, wind or sun. Since hydro power and biomass are limited by Germanys landscape and amount of arable land, the majority of electricity needs to be provided by wind and sunlight. But these sources provide energy intermittently and independently of need. Therefore both long term and high capacity storage systems will be required. A favorable energy carrier to provide this appears to be hydrogen generated through electrolysis.

Previous publications on hydrogen pathways concerning efficiency or costs often consider mobile application [1–6]

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while in recent years the focus shifted more towards the here discussed stationary application [7–11]. These studies typically use energy efficiency values for full-load operation and sometimes an estimation for the full-load hours is done to calculate the resulting costs.

In this work the authors develop a simulation tool to investigate the efficiency more in depth by using exergy and part-load models for all processes. Furthermore synthetic load profiles are generated to estimate the overall efficiency and full-load hours to then execute cost analyses of conceivable storage pathways. This detailed approach allows to identify optimization means to finally recommend further developments for the application of hydrogen as an energy carrier.

An overview of the considered processes is given in Fig. 1. Most processes can either be used in large scale, centralized plants, or in small household scale devices and also somewhere in between. The investigated pathways consist of electrolysis (alkaline, PEM and solid oxide), followed by methanation, liquefaction or compression and then following injection into the natural gas grid or a newly built hydrogen gas grid or liquid hydrogen trailer transport. The energy carrier is then used as fuel in combined cycle gas turbines or in a fuel cell (PEM and solid oxide) based combined heat and power unit.

Exergy, cost and load models

The process models and the process chains are simulated with self-programmed code in MATLAB. The only exceptions are the combined cycle gas turbine (CCGT) which is calculated with Thermoflows programs GTPro and GTMaster and the liquefaction. All substance property data is calculated with REFPROP.

The developed models are zero dimensional and consider steady state. Polarization curves from current literature are used to simulate the electrochemical cells and it is assumed that the behavior of a stack can be linearly extrapolated from the behavior of a single cell. The curves are corrected for pressure and gas composition with relations given by Ref. [12] if needed. The components for the balance of plant concerning blowers, compressors, pumps, heat exchangers, mass exchangers, reactors and burners are simulated based on their thermodynamic behavior. Heat losses are neglected except for the electrochemical cells (1.5% of ingoing energy) and the catalytic burners (2% of ingoing energy). Part load behavior of heat exchangers is estimated with a characteristic based on linearly reduced heat transfer at lower volume flows assuming turbulent flow over the whole operating region [13].

Rectifiers and transformers are considered to have a combined efficiency of 96% considering large scale application. The efficiency in part load is estimated based on the data given by Ref. [14]. The power needed for controls and remaining auxiliaries is considered to be 1% of the nominal power for fuel cells and 3% for electrolysis cells to account for product treatment [12]. The exergy model used is given by Ref. [15]. Exergy of heat, work and power as well as exergy of a steady stream of matter are considered. The latter is comprised of kinetic, potential, chemical and physical exergy. Kinetic and potential exergy differences are neglected since these are very small or nonexistent. It should be noted that chemical exergy not only considers the reaction enthalpy but also the exergy due to concentration differences of the steady stream of matter compared to the concentration in the environment. Thus also the high-purity of the water used in electrolysis and of the carbon dioxide in methanation are accounted for.

Generation

The electrolysis cells polarization curves are given in Refs. [16–18] for PEM, alkaline and solid oxide, respectively. The

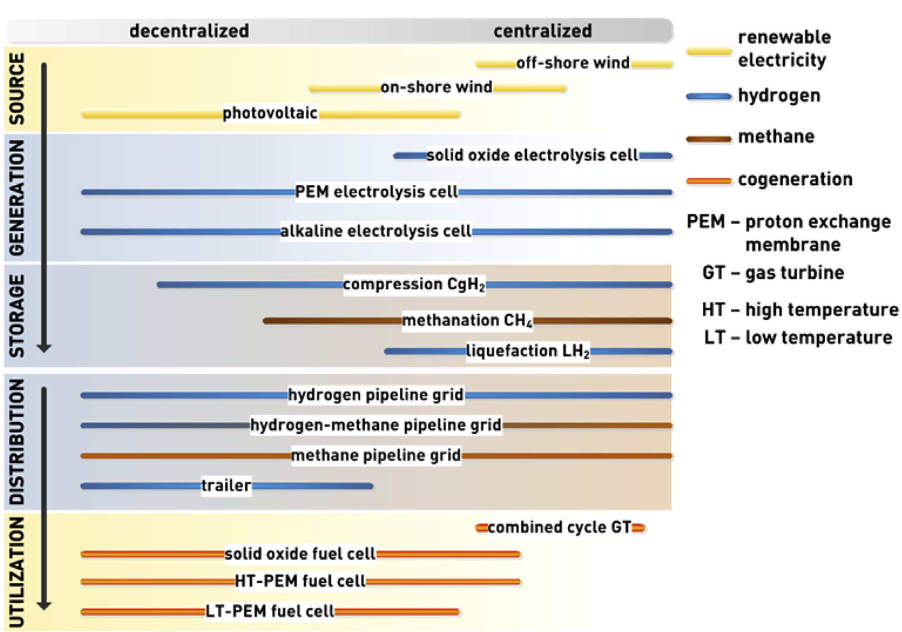

Fig. 1 – Overview of the considered processes.

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