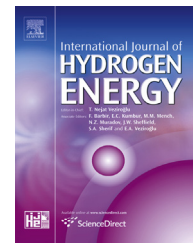




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# Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis

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## ABSTRACT

The production of hydrogen from renewable sources by water electrolysis can be coupled to a downstream chemical synthesis. This enables the production of liquid fuels or chemical raw materials that can be used in today's infrastructure. However, it is not clear which synthesis technology fits best to the novel boundary conditions for chemical plants (e.g. small scale, flexible operation). In order to identify the most promising syntheses, different one-stage synthesis systems are evaluated in terms of technology, economics and acceptance. The analysis gives in all cases production costs that are significantly above today's market prices. Fischer-Tropsch (FT) synthesis routes are expected to have a higher public acceptance compared to the other technologies due to the high product similarity to conventional energy carriers (diesel, crude oil). The economic feasibility of synthetic natural gas (SNG) production suffers from the low product price of natural gas as a benchmark, but its technical score is high. Methanol production is identified as the synthesis technology that achieves the highest overall score. The analysis shows that not only techno-economic parameters, but also parameters representing the public acceptance like the fit to the existing infrastructure, have to be considered to identify appropriate technologies that may play a role in future energy systems.

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## Introduction

In future energy systems a time dependent deviation between power generation and demand is expected due to the

implementation of renewable sources. During energy-rich times (sun is shining, wind is blowing) the production of excess electric energy is expected at locations with a high coverage of sun and wind power units. This excess electricity enables the production of hydrogen via electrolysis. Hydrogen

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can either be used directly or it can be converted to liquid fuels and chemical raw materials. The latter two options enable hydrogen storage and transport whenever there is no hydrogen infrastructure or hydrogen consumer onsite the electrolysis plant.

Since renewable electricity sources are rather distributed and have a smaller power generation capacity compared to fossil plants, today's chemical synthesis plants do not fit in terms of capacity as they have often been designed for investment cost optimization in world scale size. However, the distributed generation of excess electricity requires the development of future synthesis systems that are smaller in scale (e.g. <100 MW) and allow a more flexible operation (fast load ramps, improved part load behavior, etc.) to adapt their production rate to fluctuating energy sources.

Different synthesis products and hydrogen carriers are discussed in the literature, e.g. methanol [1], Dimethyl ether (DME) [2], gasoline [3], ammonia [4], Fischer-Tropsch (FT) fuel [5], Liquid Organic Hydrogen Carrier systems (LOHCs) [6] [7] and others.

The utilization of CO<sub>2</sub> from a coal power plant and hydrogen from electrolysis has been discussed as well. Mignard et al. calculated process efficiency and methanol production costs for different process options in the power range of 100–500 MW [8].

The production of ammonia based on water electrolysis has been analyzed by Grundt and Christiansen [4]. The energy and economic demands were compared for systems based on water electrolysis and systems based on fossil fuels. This comparison was very difficult since hydrocarbon based plants are normally in the size of 1000 t/d ammonia production, whereas a realistic size for plants based on electrolysis was 100 t/d to 500 t/d.

The University of Minnesota has developed and built up a small scale ammonia production skid that utilizes electricity from a 1.65 MW wind turbine and produces about 3.7 kg/h ammonia [9]. A life cycle assessment showed that carbon emissions are lower compared to modern ammonia production via natural gas.

In order to identify the most promising products for valorization of hydrogen from local excess renewable energy production, a techno-economic analysis is carried out and synthesis routes are compared based on an equal power input of the electrolysis (MW range) and a downstream synthesis plant. For systematic reasons, the scope of this study has been restricted to commercial products with a large industrial market and a known market price. The focus is on products that can be easily utilized in existing fuel infrastructures.

## Boundary conditions and scope of the evaluation

The present evaluation is based on an energy system with a high share of renewable sources. The scope of the analysis is shown in Fig. 1. Due to an installed over-capacity of renewable electricity production, fluctuating excess electricity is utilized in a Proton Exchange Membrane (PEM) electrolyzer. This electrolysis technology can be operated at fast load ramps, at different load points (very low minimum load and significant overload capability) and is able to produce hydrogen at high

pressure. Since the flexibility of a chemical plant is expected to be lower, a hydrogen storage system is installed that buffers the fluctuating hydrogen production and enables a more continuous operation of the connected chemical synthesis. As the hydrogen production is not within the scope of this evaluation a hydrogen supply (at 20 bar) to the chemical plant is assumed and the hydrogen production costs (incl. intermediate storage of hydrogen gas and all transportation costs between electrolysis, storage and chemical plant) are assumed to be 3 €/kg. Since the costs of hydrogen production are not analyzed in this study, the results for the different chemical routes are valid for every hydrogen supply technology (e.g. alkaline electrolysis, high temperature solid oxide electrolysis) that can provide hydrogen at these costs. Based on the DOE Hydrogen and Fuel Cells Program Record [10] hydrogen production from PEM electrolysis ranges from 4.0 USD/kg to 5.8 USD/kg. Therefore, the hydrogen supply costs to the downstream chemical plant of 3 EUR/kg used in this study can be seen as an optimistic input parameter.

Additional feed gases (CO<sub>2</sub>, N<sub>2</sub>) are purchased at market prices and are supplied from tanks. Pre-processes of these additional feed streams are not considered.

The following synthesis systems are investigated:

- Methanol synthesis
- Diesel production via Fischer Tropsch synthesis
- Syncrude production via Fischer Tropsch synthesis (without product upgrading; syncrude can be upgraded at a large scale refinery)
- Dimethyl ether (DME) production (single stage reactor configuration)
- Synthetic natural gas (SNG)
- Ammonia

Our study focuses on one-step synthesis processes due to the need of small scale and simple plant designs. Therefore, multi-stage synthesis concepts, such as Methanol-to-Olefins (MTO), Methanol-to-Gasoline (MTG) or urea production, are not considered. Carbon based syntheses are operated with CO<sub>2</sub> as the carbon source. Ammonia production is based on N<sub>2</sub> supply.

The synthesis plant is operated at 6000 equivalent full load hours per year. This is expected to be above the typical equivalent operating hours (EOH) of the electrolyzer, but significantly below today's world scale chemical plants. Further boundary conditions are summarized in Table 1. It is assumed that there are no specific boundary conditions that favor one technology over the other (e.g. natural gas pipeline onsite for the injection of SNG).

## Techno-economic analysis of the process routes

### Hydrogen-to-product efficiency

The maximum conversion efficiency is determined by the energy content of the final product compared to the energy content of the feed hydrogen. The hydrogen required per reaction product can be derived from the chemical equation

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