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Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide

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HIGHLIGHTS

- Direct use of renewable hydrogen and conversion to methane, methanol, or dimethyl ether.
- Large-scale steady-state fuel production using carbon dioxide from biogas.
- Simultaneous environmental, economic, and technical evaluation.
- All four fuels enable significant greenhouse gas and pollutant reductions.
- Combustion engine fuels considered result in similar emissions and costs.

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ABSTRACT

Hydrogen (H_2) production through water electrolysis is widely discussed as a means of storing renewable electricity in chemical bonds. Hydrogen can be used for transportation in fuel cell vehicles, but it can also be reacted with carbon dioxide (CO_2) to form other fuels. While many concepts have been proposed, detailed comparisons of different pathways are still scarce. Herein, we present a technical, environmental, and economic comparison of direct H_2 use in fuel cells, and production of methane, methanol, and dimethyl ether (DME) for use in internal combustion engines for light-duty vehicle applications. The scenario considered uses renewable electricity for water electrolysis, and CO_2 which is supplied continuously from biogas upgrading. All four fuels enable significant reductions (79–93%) in well-to-wheel greenhouse gas emissions as well as pollutant formation compared to fossil fuels, but they require very cheap H_2 to be competitive to fossil fuels, confirming intuitive expectations. While direct use of H_2 has obvious advantages (no conversion losses, high efficiency of fuel cells compared to internal combustion engines) in terms of overall electricity consumption, emissions, and fuel cost, its drawbacks compared to the other fuels are the need for an H_2 infrastructure, the high fueling pressure, and lower driving range. Among the three combustion engine fuels, DME has the lowest fuel cost and electricity consumption per distance driven because of the more efficient use of H_2 in its production, as well as the highest volumetric energy density, while methane has slightly lower greenhouse gas emissions. Cost and energy demand are dominated by H_2 supply, meaning that integrated solutions could be more attractive than separate electrolysis and fuel production.

1. Introduction

Transportation currently accounts for more than a quarter of the world end-energy use and causes a similar fraction of the anthropogenic greenhouse gas emissions, with significant future growth expected [1]. This motivates the search for more sustainable alternatives to

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conventional transportation concepts that are largely based on fossil fuels. Battery electric vehicles charged using renewable electricity are being discussed as a promising alternative for short-distance transportation. However, long-distance transportation is likely to continue to rely on liquid or gaseous fuels in the near-to-mid term future because of the required storage capacities [2].

Hydrogen (H_2) is being discussed both as a fuel and as an intermediate in the production of a variety of organic fuels [3]. Since it can be produced via water electrolysis, it also provides a means of coupling the electricity and transport sectors [4,5]. Electrochemical production has thus been suggested as a means for utilizing fluctuating renewable electricity and providing chemical energy storage [6,7], as well as providing renewable energy for other industries in both grid connected and isolated configurations [8]. Direct use of H_2 as a fuel has obvious advantages since it avoids further conversion losses and allows for high tank-to-wheel efficiencies when used in fuel cell vehicles. However, it requires a dedicated H_2 infrastructure for distribution and storage as well as a fleet of fuel cell vehicles [9]. Therefore, there has been increasing interest in recent years in the conversion of H_2 to organic fuels that are more compatible with the current distribution infrastructure and vehicle fleet.

In order to produce organic fuels, H_2 has to be combined with a carbon source. One option is to use carbon dioxide (CO_2), which can, at least in principle, either be extracted directly from the atmosphere [10] or captured from point sources. The latter can include fossil power plants, other fossil anthropogenic sources (e.g., chemical processes with an inherent production of CO_2) [11], or biogeneous sources (e.g., CO_2 that occurs as a byproduct in biogas production) [12,13].

So far, the discussion of the production of synthetic fuels from renewable H_2 and their application in transportation has mostly either been focused on specific routes (e.g., methanation [14,15], methanol production [16], or ammonia production [17]), on certain technical aspects relevant to different routes (e.g., catalysts [18]), or on region-specific analyses for energy system integration (e.g., [19,20]). Existing well-to-wheel (WTW) analyses comparing different fuels, on the other hand, often did not consider hydrogen-based synthetic fuels in detail [21,22]. The recent studies of Connolly et al. [2], Grahn et al. [23,24] and Tremel et al. [25] did include H_2 and derived fuels in their energetic and economic analyses. However, their evaluations do not include a well-to-wheel greenhouse gas (GHG) analysis. On the other hand, Matzen and Demirel [26] and Sternberg and Bardow [27,28] did provide a life cycle assessment for different fuels produced from renewable H_2, but they did not consider fuel production cost. Parra et al. [29] conducted a thorough techno-economic and environmental study of hydrogen and methane production for energy storage, but they do not consider transport applications or compare to other synthetic fuels.

Data compiled from such separate studies is not necessarily suitable for direct comparison because they are based on different assumptions and use very different levels of detail. This was recently highlighted by Artz et al. [30] in their comprehensive review of life cycle assessments for CO_2 utilization and by Brynolf et al. [24] in their review of production costs estimates for electrofuels. In this context, Albrecht et al. [31] recently advocated the use of a standardized methodology for improving comparability of techno-economic assessments of alternative fuels. This is certainly even more desirable when combining both techno-economic and life cycle analyses in order to provide a more comprehensive picture that can aid decisions towards practical implementations or guide further applied research. To this end, such an analysis should also contain a discussion of engine performance and the key factors affecting the performance of the fuel production processes, which is lacking in most system level studies.

Therefore, the purpose of the present article is to give a combined technical, environmental, and economic evaluation of different alternatives for introducing renewable H_2 into the transportation sector. The evaluation is based on a set of common assumptions and considers both the conversion processes for fuel production and the application in transportation. Beside direct use of H_2 in a fuel cell, we consider conversion to methane and methanol for use in spark ignition engines, as well as dimethyl ether (DME) for use in compression ignition engines. Specifically, the goal is to provide insight into the factors determining the overall performance of the process chain. The list of fuels considered is not intended to be exhaustive, but is instead limited to a few promising concepts for which sufficiently detailed information is available on both production processes and engine performance. Hence, the selected fuels are considered to be reasonably close to practical application.

In the following, we first give some details on the scenario and the assumptions used and the selection of fuel candidates considered, and describe the methods used for the evaluation. Next, the performance of processes for converting H_2 into methane, methanol and DME is discussed, and the entire process chains for the different fuels are evaluated according to their fuel cost and well-to-wheel greenhouse gas emissions. Finally, these analyses are combined with an evaluation of the performance of the different fuels from an application perspective including aspects related to engine performance, safety, and infrastructure.

2. Methods and assumptions

Four different options for introducing renewable H_2 into the transport sector are assessed by comparing state-of-the-art process chains with different fuels for one specific scenario (Fig. 1).

2.1. Scenario and selection of fuel candidates

For the present study, we assume that H_2 is produced from renewable electricity via electrolysis, stored in a cavern storage facility, and delivered continuously to a centralized large-scale fuel production plant (where applicable) or gas stations through a pipeline at a final pressure of 70 bar. As a carbon source, we assume the use of CO_2 that occurs as a (currently unused) byproduct of biogas upgrading [33]. From the fuel production plant, the fuel is transported to gas stations either via pipeline (CH_4) or via truck (MeOH and DME). For direct use of H_2, the energy demand reported by Grube et al. [32] for pipeline transport to the fuel production plant is taken to represent the distribution to gas stations via pipeline instead. At the gas stations, CH_4 and H_2 have to be further compressed to their respective fueling pressures (Table 1). All steps except for electrolysis are assumed to operate at steady state using grid electricity.

In a study considering Germany in 2035, Grube et al. [32] estimated that 1.9×10^5 t/a of H_2 can be produced utilizing renewable electricity that would otherwise curtailed in northern Germany (which has a high concentration of wind power), because it cannot be utilized, stored, or transported elsewhere at the time of production. Depending on the fuel to be produced, the required amount of CO_2 for converting this H_2 is between 1.0×10^6 t/a and 1.4×10^6 t/a, which is roughly 10% of the envisioned availability of CO_2 from biogas upgrading in Germany in

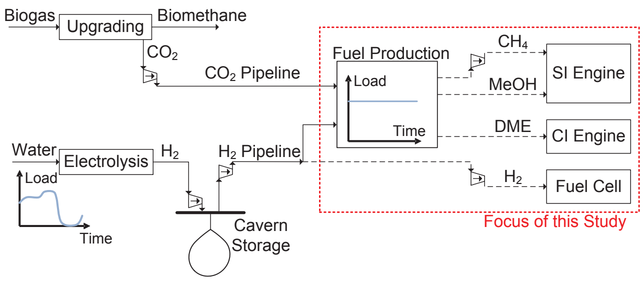

Fig. 1. Pathways considered in this work. Hydrogen production via electrolysis is assumed to operate dynamically using renewable electricity [32]. All other steps operate at steady state and use grid electricity.