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Hydrogen mobility from wind energy – A life cycle assessment focusing on the fuel supply

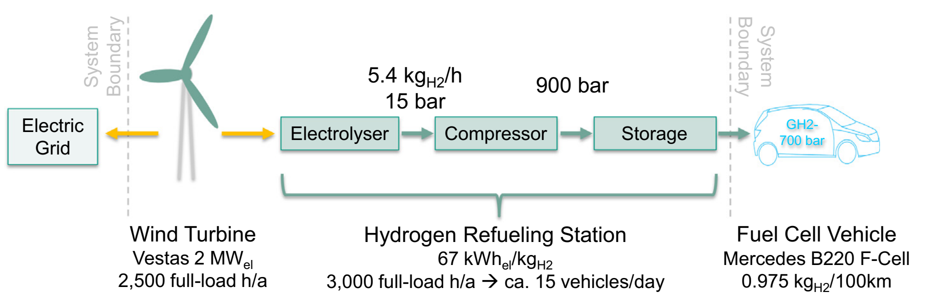
Jörg Burkhardt [a,*], Andreas Patyk [a], Philippe Tanguy [b], Carsten Retzke [c]

[a] Karlsruhe Institute of Technology (KIT), Institute for Technology Assessment and Systems Analysis (ITAS), Karlstraße 11, 76133 Karlsruhe, Germany
[b] Total S.A., La Défense 6, 2 Place Jean Millier, 92078 Paris La Défense Cedex, France
[c] Total Deutschland GmbH, Jean-Monnet-Straße 2, 10557 Berlin, Germany

HIGHLIGHTS

- Environmental performance, focusing on production and provision of hydrogen.
- Primary data collected from a 700 bar refueling station incl. alkaline electrolyser.
- Construction of facilities dominates the primary energy demand and emissions.
- Refueling station contributes to same extent to GHG emissions as electricity supply.
- Remarkably high expenditures for provision of supplies.

GRAPHICAL ABSTRACT



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ABSTRACT

In the current debates on reducing greenhouse gas emissions in the mobility sector, hydrogen produced via water electrolysis from renewable electricity is commonly regarded to be a sustainable energy carrier with large potential for decarbonisation of the mobility sector. Directly produced at the refueling stations site, hydrogen greenhouse gas emissions are presently defined to be zero in e.g. the Directives of the European Union since emissions arising from the facilities construction are defined to be negligible. In order to check the validity of this assumption with respect to the latest technical developments in hydrogen supply, the present article aims to report the environmental performance of hydrogen being produced and compressed for mobility purposes. To this end, a state-of-the-art hydrogen refueling station (HRS) with an on-site alkaline electrolyser is assessed, which was built and operated in Berlin. Assuming electricity supply from wind energy generation, a life cycle assessment for the complete value chain was carried out where primary data for the build-up of electrolyser and HRS were obtained during decommissioning of the station.

The results show that the construction of HRS and on-site electrolyser requires higher material and energy expenditures compared to previous investigations on similar but technically less advanced systems. These expenditures generate a significant footprint in the specific e.g. greenhouse gas emissions if the electrolyser is operated at a reduced load factor as it may be foreseen for grid stabilisation purposes. To ensure a strong reduction of emissions compared to conventional fuels, this load factor should be

Abbreviations: CED, cumulative energy demand; FCEV, fuel cell electric vehicle; GHG, greenhouse gas; HHV, higher heating value; HRS, hydrogen refueling station; ICE, internal combustion engine; LCA, life cycle assessment; LCIA, Life Cycle Impact Assessment; NR, non-regenerative.

* Corresponding author at: c/o Anna-Louisa-Karsch-Straße 2, 10178 Berlin, Germany.
E-mail addresses: joerg.burkhardt@kit.edu (J. Burkhardt), andreas.patyk@kit.edu (A. Patyk), philippe.tanguy@total.com (P. Tanguy), carsten.retzke@total.de (C. Retzke).

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sufficiently high and should be defined to not fall under a certain threshold in upcoming directives. Besides, excessive use of supplies should be avoided and the refueling station should be operated with renewable electricity to the largest extent.

1. Introduction

To fulfil the European Union goals for reduction of greenhouse gas (GHG) emissions by 80% in 2050, Germany foresees to have at least 80% of its electricity production being supplied by renewable resources [1,2]. In 2014, electricity from renewables already contributed to 25.8% of Germanys gross electricity production [3], leading to temporarily production of electricity that exceeded the capacity of the electric grid in some regions. In this case, electricity production from wind turbines and PV modules is curtailed. In 2014, this amount of excess electricity was 1581 GWh_{el} [4] which corresponds to the yearly electricity production of ca. 320 state of the art wind turbines (nominal power of 2 MW_{el}, 2500 full-load hours). 77% of this excess electricity was actually produced by wind turbines [4].

There is a wide consensus throughout the German energy economy that the amount of excess electricity is going to increase with the further transition of the energy system. Strongly depending on the assumptions made, a negative residual load in the electric grid is predicted to occur between 2100 and 4000 h/a by 2030–2050 in several studies [5–7]. Having electrolysers installed to balance the loads in the electric grid, this negative residual load is discussed to be used for water electrolysis.

To decarbonize the mobility sector, the use of the produced hydrogen in the mobility sector is discussed. Even though the penetration of fuel cell cars in Germany is limited nowadays, there are 50 hydrogen refueling stations (HRS) to be installed by the mid of 2016 [8]. By 2023, the installation of 400 HRS is foreseen by the H2 Mobility initiative [9].

1.1. Former investigations on wind electrolysis and hydrogen supply

The use of hydrogen in energy applications does not cause direct emissions, of e.g. greenhouse gases, since hydrogen reacts to water when it is oxidised. However, emissions occur during the production, compression and storage of hydrogen, e.g. due to the use of fossil fuels for operation and construction of the whole facilities.

A considerable amount of studies have been carried out to determine these emissions occurring from hydrogen mobility with hydrogen being provided from water electrolysis. Regarding the direct production of hydrogen at the HRS site, interesting results have been published in life cycle assessments carried out by Spath and Mann [10], Maak [11] and Patterson et al. [12].

Spath et al. consider a system comprising an electrolyser (30 Nm^3/h) being fed by three 50 kW_{el} wind turbines and a HRS delivering hydrogen at 200 bar. They showed that the majority of emissions originate from the systems construction, with the wind turbines having the largest contribution (78%) to the systems specific GHG emissions of 0.97 $kg_{CO2\text{-}equ}/kg_{H2}$. Patterson et al. consider a similar system (30 kW_{el} wind turbines, 350 bar HRS). They use however a different kind of methodology making a direct comparison of results quite complex.

Maak et al. assume their electrolyser (60 Nm^3/h) to be fed with a European electricity mix and to be operated with a capacity factor of nearly 100%. They conclude that emissions are mainly driven by the electricity supply and could be shifted to the construction phase if electricity was supplied by renewable sources.

Additional studies on wind electrolysis have been published in [13–19]. The majority of these studies refer to results or material inventories from [10,11] or use restricted (or not traceable) databases. Regarding technical parameters of hydrogen refueling stations in the reviewed literature, hydrogen is mostly considered to be compressed and dispensed at 200–400 bars. In contrast, hydrogen is nowadays mostly foreseen to be compressed to up to 900 bars to achieve a pressure of 700 bars inside the vehicles tanks [20,21]. Even though hydrogen mobility is widely investigated for different HRS sizes and pressure levels in major mobility studies, e.g. in [22,23], construction of plants and facilities is mostly neglected in these studies. A specific hydrogen refueling station is also not considered in [24] or [25]; conventional stations are assumed instead.

Additionally, electric output powers of often regarded wind turbines (30–50 kW_{el}) may not reflect the state of currently installed wind turbines, having e.g. average electric powers of about 2500 kW_{el} in Germany (2012) [26].

1.2. Goal of the study

The above shows clearly that the availability of primary data on wind electrolysis systems is very limited; the majority of investigations rely on data from few investigations. A similar outcome is found in [27], carrying out a literature review on 21 electrolysis studies and stating that Spath and Mann [10] is "the major data source for every paper discussing LCA of wind based electrolysis". Additionally, environmental burden for providing hydrogen by 700 bars HRS are incompletely addressed in literature since expenditures arising from the construction of these HRS are not explicitly regarded due to a lack of primary data. This is covered by [25].

The aim of this paper is to assess the environmental impact related to the production of hydrogen and its dispensing to state of the art fuel cell electric vehicles. Being embedded in an energy system with a high share of intermittent electricity production, hydrogen is assumed to be produced from water electrolysis fed by excess electricity from wind turbines. To catch up with the current state of technology, a modern wind turbine and a 700 bar HRS including an on-site electrolyser being installed and operated in Berlin, Germany, are assessed. In order to provide a valid database, data were collected from the HRS documentation and measurements during the HRS decommissioning. Since primary data on the build-up of the electrolyser and HRS were obtained in the framework of this study, the actual work contributes to fill an important data gap. Besides addressing the scientific community, the article addresses policy makers to classify environmental implications being predominantly related with the facilities construction, which is mostly neglected in major mobility studies. Environmental burdens are assessed with a special view on the influence of embedding the regarded technology in an energy system with high shares of renewable electricity production, which is currently not covered in literature.

2. Methods

2.1. Environmental life cycle assessment (LCA)

For investigating the environmental impact, a life cycle assessment of the system has been carried out. Life cycle assessments (LCAs) are compilations and interpretations of