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Carsharing with fuel cell vehicles: Sizing hydrogen refueling stations based on refueling behavior

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HIGHLIGHTS

- Data on refueling behavior in free-floating carsharing are provided.
- An optimization methodology for sizing hydrogen refueling stations is presented and applied.
- Results show that carsharing fleets induce a reduction of hydrogen production costs.
- Oversizing hydrogen refueling stations to also serve private cars in the future does not increase costs significantly.

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ABSTRACT

Fuel cell vehicles and carsharing depict two potential solutions with regard to pollution and noise from traffic in cities. They are most effective when combined, and hydrogen is produced via electrolysis using renewables. One major hurdle in utilizing fuel cell vehicles is to size hydrogen refueling stations (HRS) and hydrogen production via electrolysis properly in order to fulfill the carsharing vehicles' demand at any given time. This paper presents data on refueling behavior in free-floating carsharing, which have not been available thus far. Refueling profiles of hydrogen carsharing vehicles are modeled based on this data. Furthermore, this analysis presents and applies a methodology for optimizing topology of a wind turbine-connected HRS with onsite electrolysis via an evolutionary algorithm. This optimization is conducted for different carsharing fleet sizes, and HRS profitability is evaluated. The results show that larger fleets are capable of decreasing hydrogen production costs significantly. Moreover, adding capacity to the HRS in order to prepare for hydrogen demand from private vehicles in the future does not significantly increase costs. However, overall costs are still high compared to the current market price in Germany, requiring further cost reductions.

1. Introduction

Currently, transportation accounts for a significant share in CO_2 emissions worldwide as well as in Germany [1,2]. Additionally, cities are struggling with high air pollution due to vehicle tailpipe emissions, leading to discussions about banning vehicles, especially diesel cars, from inner cities. Thus, in order to maintain personal mobility and regain a higher air quality in cities, a transportation transition is required. According to Agora Verkehrswende [3], this transition can be perceived as change in mobility behavior on the one hand and energy transition in the transportation sector on the other hand. One approach of providing mobility more efficiently is carsharing, which can reduce the number of cars on the road if substituting privately owned cars. In contrast, energy transition in transportation requires vehicle concepts capable of using renewables as an energy source. One of the most promising options in this regard are fuel cell electric vehicles (FCEV) fueled by hydrogen. Thus, especially the combination of both approaches, carsharing and FCEV, might become an important means in order to deal with the aforementioned problems. This approach already has been applied in recently emerged projects in major cities in Germany (see literature review in Section 2.1). But hydrogen refueling infrastructure is scarce and needs to be complemented if carsharing vehicles demand hydrogen

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at a larger scale. This raises the question of how hydrogen refueling stations (HRS) for carsharing should be designed in terms of hydrogen production and storage capacity, and which costs these stations are associated with. Therefore, this study presents data on refueling behavior of free-floating carsharing vehicles in six German cities collected over a period of seven months. Based on these data, this paper provides a novel and comprehensive approach of sizing hydrogen refueling stations with onsite electrolysis. It is applied to a case of combined hydrogen demand of private and carsharing vehicles and optimizes hydrogen production costs.

The remaining part of this section gives an overview of carsharing and hydrogen as a fuel, while Section 2 provides a literature review. Sections 3 and 4 describe the methodology and the investigated scenarios, respectively. Results are presented and discussed in Section 5, followed by conclusions in Section 6.

1.1. Carsharing

The concept of carsharing allows people to use one car or a pool of cars collectively in a sequential manner. Thus, taking part in carsharing might make owning a car unnecessary. This can lead to lower mobility costs for carsharing users, especially if access to a vehicle is not required regularly. Additionally, carsharing is also beneficial to the respective city and the environment since congestion can be reduced, and people are encouraged to use public transportation more often if they do not own a private car. There are different forms of carsharing: private carsharing, station-based carsharing and free-floating carsharing. Private carsharing is organized by the users themselves, for example, when two neighbors share one vehicle. In contrast, station based and free-floating carsharing are commercial services provided by a company. In most cases, users have to register to the service and can book cars online. They are either charged by distance traveled or by duration of driving. Vehicles of station-based carsharing are parked at selected, designated spots and have to be returned to these spots after usage. Free-floating carsharing, on the other hand, does not require the use of discrete spots for fetching and parking a vehicle. Instead an area of operation within a city is specified. Customers are allowed to park carsharing vehicles wherever they want within this area, so in general, cars are spread out among this area. According to [4], more than 2 million drivers were registered to a carsharing service in Germany by 01.01.2018, which is an increase of 23% compared to the number of registered users by 01.01.2017. These people share nearly 18,000 carsharing vehicles and account for 3.3% of all people holding a driver's license [5].

1.2. Hydrogen as a fuel

FCEV are electric vehicles using pressurized, gaseous hydrogen as an energy carrier. Hydrogen and oxygen are converted onboard into water vapor and electric energy, propelling an electric motor. Thus, instead of harmful tailpipe emissions, there are potential indirect emissions during hydrogen production. In fact, today most HRS rely on delivered hydrogen originating mostly from fossil fuels for cost reasons. In order to achieve a significant reduction of CO_2 emissions, it is therefore important to produce hydrogen via electrolysis using electricity from renewable energy sources. Especially in the initial phase of low market penetration of FCEVs, it can be favorable to utilize electrolysis onsite HRS and avoid central scaled-up hydrogen production and delivery by truck [6]. In other scenarios with a higher overall hydrogen demand, other options like central electrolysis and delivery might become favorable. Besides onsite electrolysis, HRS consist of hydrogen storage tanks at low (~45 bar) and high (~1000 bar) pressure, a hydrogen compressor, and a dispenser including a hydrogen precooler. Using additional cascades of storage tanks can be advantageous in terms of energy consumption [7]. Another established method of storing hydrogen is in liquid form, which requires liquefaction in the first place [8]. In the future, hydrogen storage based on liquid organic hydrogen carriers might be an additional option [9,10]. In Germany, there are to date less than 40 HRS, but the network is growing continuously. Currently, 48 additional stations are under construction, contributing to the target of 100 HRS by 2019 [11]. Due to the low number of FCEV currently on the road, HRS in general suffer from underutilization and cannot be operated profitably. FCEV fleets, like taxis or carsharing fleets, can increase utilization and profitability of HRS, but require additional capacity if deployed in larger numbers. Hydrogen production can be adapted to energy provision from renewables and thus be a means of flexibility to the overall energy system [12,13,1,14–17]. This flexibility can be especially valuable, when harnessing surplus energy from wind farms [18–20]. Moreover, large scale energy storage can be accomplished at lower costs when using hydrogen storage systems compared to electrical energy based storage systems [21]. Hydrogen is also discussed as a flexible energy carrier for micro grids, used for stationary or mobile applications as well as for storage purposes [22–25].

2. Literature review

The following literature review focuses on the main aspects of this paper: hydrogen based carsharing (Section 2.1), driving and refueling patterns of carsharing drivers in general (Section 2.2), and hydrogen refueling stations (Section 2.3). This chapter concludes with the main contributions of this paper as they contrast with the previously analyzed literature (Section 2.4).

2.1. H2-Carsharing

Literature on hydrogen based carsharing is sparse. Kriston et al. [26] analyzed carsharing with FCEV in Budapest, Hungary in terms of economy. They investigated fleet sizes between 20 and 200 microcars. The investigation focused on business models, and neither the refueling process nor refueling behavior were taken into account. Furthermore, HRS were not part of the analysis.

In fact, there are already two carsharing services in Germany that make use of FCEV in their fleet: BeeZero and CleverShuttle. BeeZero is located in Munich and is a mixture of station-based and free-floating carsharing service. Vehicles are distributed across the city, which is divided into several zones. Customers are required to return the vehicle in the respective zone in which they rented it. The vehicle fleet consists of 50 FCEV [27].

CleverShuttle, by contrast, is a German ridesharing service, so actually it is not a conventional carsharing service. Customers can order a vehicle as they would order a taxi, and additional customers with similar destinations can join the ride en route. Thus, rates are lower than conventional taxi fees. Recently, CleverShuttle integrated 20 FCEV in their fleet in Hamburg [28] and 10 FCEV in Stuttgart [29].

2.2. Driving and refueling patterns

Schmöller et al. [30] analyzed free-floating carsharing operation with conventional vehicles in Munich, Germany. They evaluated hourly data on booking profiles between November 2011 and October 2013. While this provides insights into temporal mobility demand, neither hydrogen as a fuel nor refueling patterns were investigated.

In contrast, Lopes et al. [31] focused on station-based carsharing. Driving patterns are approximated via agent-based simulation. Their model combines survey data on mobility behavior in Lisbon, Portugal with stochastic methods in order to vary temporal trip probability. Refueling was assumed to be taken care of by the carsharing operator, and refueling patterns were not discussed. Moreover, their approximated results do not match the findings of [30].

The study "Urban mobility in Transition" [32] examined changes in urban mobility markets that are based on the example of free-floating