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Vehicle Scheduling and refueling of Hydrogen Buses with On-site Electrolysis

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Abstract: In this paper, we present the first model for hydrogen-fueled bus fleet operation with on-site hydrogen production. To support the planning and operation of municipal hydrogen bus fleets, we transfer and adapt a vehicle scheduling algorithm for conventional buses. We optimize vehicle routes with regard to minimizing operational costs. Based on that, we implement a hydrogen refueling strategy suited to minimize the peak demand for a hydrogen refueling station with on-site electrolysis. To demonstrate the functionality of the approach, it is applied to a real-world scenario for public transport in Karlsruhe, Germany. The findings show that the scheduling strategy for vehicle routing and fueling is suited to reduce peak hydrogen demand and thus the required electrolyser capacity and associated costs. In comparison to a naive benchmark refueling scenario, the peak demand is reduced by 20%, lowering investment costs by 400,000 €.

Keywords: hydrogen mobility; transport scheduling; fuel station operation

1 Introduction

The worldwide efforts to mitigate climate change represent a specific challenge for the mobility sector. Germany has set the target of reducing mobility-related greenhouse gas emissions by at least 40% percent until 2030, compared to 1990 [BM19]. However, while the electricity sector is on the path to integrating renewable power sources, the share of mobility based on renewable resources remains low [Ge20]. A sustainable energy transition therefore would profit largely from using low emission electricity in the mobility sector. One promising avenue to use more of such renewable electricity in the mobility sector is hydrogen. Especially heavy-duty vehicles, including buses, trucks and trains, benefit from hydrogen's high gravimetric energy density and the ability for fast recharging. In first field tests, hydrogen buses for local public transport have proven well equipped to contribute to a sustainable city development [NO18]. A key prerequisite for the successful proliferation of hydrogen buses is an efficient operation of hydrogen supply and bus refueling. On-site hydrogen production from electrolysers can convert electricity, ideally with a high share of renewables, into sustainable hydrogen that can be used directly at the fuelling station. This also reduces the need for fuel transportation. With a large bus fleet and predictable

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operation schedules, public transport companies are especially suited for the implementation of hydrogen buses and an according refueling strategy. It has already been shown that renewable hydrogen can be produced cost competitively in certain locations in Germany [GR19]. However, this finding neglects the demand side. It is assumed that hydrogen will be used at the time and location, where it is produced. To complement this picture, we examine the operation of a hydrogen bus fleet in the municipal transport sector in an integrated approach, thus linking local production and local demand. To this end, we address two research questions:

(1) How can hydrogen-based bus transport with on-site electrolysis be modelled?

(2) How much electrolysis capacity and investment costs can be saved by applying this model in a real world scenario of a municipal fleet with 24 buses?

To answer these questions, we structure this paper as follows: First, we model a vehicle-scheduling problem to optimize the driving distances within each route and to determine the allocation of routes to the hydrogen buses. We solve this problem using flow optimization and set partitioning. The data required for this step includes departure and arrival times as well as the trip lengths, speed limits along the route and the location of the refueling depot. The resulting routes are modelled as time-space-graphs as proposed in [GKS05; KMS06]. In the second stage, we use actual bus schedules of a local public transport provider in the German city of Karlsruhe to demonstrate the applicability of the model. We use our proposed approach to model the scheduling of the bus fleet that comprises all bus lines starting or ending at a distance of three kilometers around the town center. The actual driving distances, as well as the distance to the refueling depot are calculated using the 'OpenStreetMap' software [HW08]. The dimensioning of the electrolyser is one of the peculiarities to consider for the on-site production of hydrogen for a hydrogen bus fleet. With investment costs of 1100 € per kWp [Bö20], electrolysers are one of the cost drivers for hydrogen fuel stations. For a sub-sample of 24 buses on eleven bus lines, we investigate a vehicle scheduling algorithm with regard to a minimized electrolyser capacity and this reduced investment costs. Our results show that an optimal scheduling and refueling of hydrogen buses can reduce the required peak hydrogen production capacity by 20% compared to a naive strategy with uncontrolled refueling. In the example scenario, this reduces the investment costs for the electrolyser by 400,000 €.

2 Related Work

Our work builds on two major strands of literature – the operation of hydrogen refueling stations and the optimization of vehicle scheduling. In this subsection, we briefly review this literature. A hydrogen refueling station generally consists of four system components: The hydrogen production, storage, supply and conditioning. Production of hydrogen can be done either off-site, or on-site. In the case of on-site production the costs for hydrogen delivery can be omitted. If hydrogen is produced via water electrolysis it can be emission-free if electricity from renewable energy sources is used. The two predominant storage technologies for hydrogen are liquid hydrogen (at cryogenic temperatures of approximately -253 °C and low pressure) or compressed gaseous hydrogen (at ambient temperature and high pressure) [Fi17]. In contrast to liquid fuels, hydrogen cannot simply be pumped into the tank, but is either gradually released into the vehicle tank through pressure compensation or a booster-compressor [SVS13]. The investment costs of the chosen electrolyser, storage technology and filling equipment typically make up a considerable share of total hydrogen costs [Al16; Gr17]. Recently, first studies on hydrogen fuel stations have analysed siting, sizing and operation. Sun et al. [Su19] optimize the location and size of hydrogen refueling stations in Chengdu, China. However, the model does not consider the station operation and the temporal aspects of refueling, and instead just covers the demand of one year. Similarly, Yang and Jiang [YJ20] optimize the location and capacity of hydrogen refueling stations, considering uncertainty of long-run hydrogen demand, but no temporal resolution of refueling events. Focusing on hydrogen-powered freight-trucks, Rose and Neumann [RN20] optimize the location of refueling stations with on-site electrolysis using grid electricity. They analyse a case study for German highways in 2050, utilizing truck driving data at hourly resolution. To our knowledge, all existing hydrogen fuel station studies take hydrogen demand patterns as given and try to adequately design hydrogen supply. Moreover, no study has yet specifically analysed hydrogen refueling stations for public transport. This use case poses particular requirements, as station operation and driving schedules need to be aligned. Vehicle scheduling describes the task of optimally distributing a specified number of given trips to the vehicles of a fleet [BK09]. It plays a central role in operational planning in public transport. The desired result of a vehicle scheduling optimization problem is a schedule that contains all tours of all vehicles. Each tour is a number of trips that start and end at a depot. In the case of public transport, the depot typically includes the infrastructure for refueling. An overview of vehicle scheduling problems is given in [BK09]. An overview of optimal vehicle scheduling for public transport can be found in [KMS06]. Vehicle scheduling problems in public transport can be categorized based on characteristic properties of their problem instances. A first distinction is made with regard to the number of depots within the transport network under consideration, namely between single depot and multi depot setups. While multi depot setups represent NP hard problems, single depot models can be solved in polynomial time [KMS06]. The system in our case study relies on one central single depot. Furthermore, mathematically, vehicle scheduling can include flow models and assignment problems [BK09]. Compared to conventional bus fleets, the operation of hydrogen-fueled fleets with on-site electrolysis requires consideration of additional constraints. In contrast to conventional refueling stations, hydrogen refueling stations can only serve a smaller number of refueling events in a given period. More importantly, conventional fuel stations can rely on regularly filled fuel storage, whereas hydrogen fuel stations with on-site production rely on the production capacity of the electrolyser. Unscheduled refueling requests from buses at the depot cause variable demand, whereas the on-site hydrogen production rate is preferably constant to achieve the highest efficiency of the electrolyser [HK18]. In addition, investment costs are an essential cost factor for hydrogen mobility. Since the electrolyser has to be sized to satisfy maximum demand from buses, the refueling schedule directly impacts the total

		Index	
b	Bus index	B	Set of buses in the fleet
i, j, k	Node indices	V	Set of nodes in the network
e_{ij}	Edge of a network	E	Set of edges in the network
t	Time step index	T	Time horizon
		Variables	
c_{H2}	Hydrogen fuel costs	Q	Cost factor for waiting during a trip
C_{ij}	Weight of edge e_{ij}	T^f	Hydrogen refueling time
D_{ij}	Length of edge e_{ij}	$\overline{V}^e$	Average empty driving velocity
$E^t, E^w,$	Amount of trip, waiting	W_{ij}	Waiting duration on edge e_{ij}
E^d	and depot edges	x_{ij}	Flow on edge e_{ij}
E^s	Number of scheduled trips	y_{ijb}	Assignment of x_{ij} to the trip of bus b
Fij	Trip frequency	z	Electrolyser capacity
h_{bt}	Hydrogen refueling of b in t	α_{bt}	Binary variable, indicating
H^d	H_2 consumption of a bus		if bus b is in the depot at t
	per kilometer	β_{bt}	Binary variable, indicating
H^{max}	Maximum H_2 refuel capacity		if bus b is refueled at t

Tab. 1: Nomenclature

costs of the infrastructure. The refueling of vehicles with hydrogen must therefore already be taken into account in the route allocation and deployment planning of the vehicles. This motivates to schedule vehicles in a way that distributes refueling events as uniformly as possible, while meeting all mobility needs. In the following section, we develop a specific vehicle scheduling model for hydrogen buses that takes these unique aspects into account.

3 Methodology

In this section, we describe the procedure for modelling the vehicle scheduling problem of a hydrogen fueled bus fleet for public transport in combination with on-site electrolysis.

3.1 Time-Space Modeling

To assess the hydrogen demand and refueling frequency of a hydrogen bus fleet, we determine the bus driving distances and trip durations for each bus line. The round trip modeling for the entire bus fleet is based on the time-space modeling methodology presented by Kliewer et al. [KMS06]: First, a time-space network is set up for the trips within the transport network. The network serves as input for a two-step solution of flow optimization and subsequent flow decomposition. The two-step approach allows the determination of optimal routes and optimal assignment of trips along the routes to the vehicles of the fleet. Figure 1 shows a simple example of a time-space graph with one depot ('D') and two

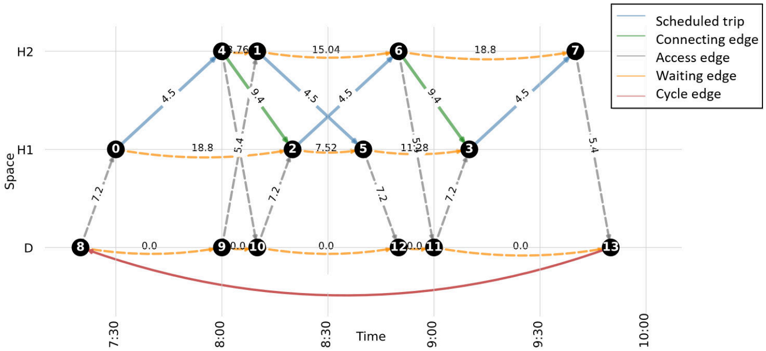

Abb. 1: A simple time-space modeling example with one depot and two stops

stops ('H1' and 'H2'). On the basis of the time-space network, an optimal trip schedule is determined. For this purpose, a flow problem is set up [6]. The goal of flow optimization is to determine the flow x_{ij} for each edge e_{ij} of the network in such a way that all planned timetable trips are completely executed while minimizing the operational costs, consisting of waiting costs and fuel costs. The costs of all edges are given by:

$$C_{ij} = \begin{cases} D_{ij} H^d c_{H2} & \forall e_{ij} \in E^t \\ W_{ij} Q & \forall e_{ij} \in E^w \\ 0 & \forall e_{ij} \in E^d \end{cases} \tag{1}$$

The flow determination is given by:

$$\min \quad \sum_{(i,j)\,|\,e_{ij} \in E} C_{ij} x_{ij} \tag{2}$$

$$s.t. \quad \sum_{j\,|\,e_{ij} \in E} x_{ij} - \sum_{k\,|\,e_{ki} \in E} x_{ki} = 0 \qquad \forall\, i \in V \tag{3}$$

$$x_{ij} = F_{ij} \qquad \forall\, (i,j)|e_{ij} \in E^s \tag{4}$$

$$x_{ij} \in \mathbb{N} \tag{5}$$

The objective function is the minimization of the sum of the costs of all flows. The conservation of flows at each node is ensured by Equation (3). The flow conservation guarantees that in a solution the sum of all incoming flows equals the sum of all outgoing flows at each node. In addition, the determined flow on the trailing edge corresponds to the number of vehicles used in the optimal solution, as all vehicles drive back to the depot at the end of the modelled period and reach the beginning of the next period via a circulation edge [KMS06]. The period in this context is the time horizon over which the scheduling is modeled. Equations (4) and (5) ensure that the flow solution contains all planned timetable trips and has a non-negative integer value.

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[6] For basics of flow modeling we refer to [Ta07].

3.2 Operation and Scheduling of a Hydrogen Bus Fleet

For a complete solution of the vehicle scheduling problem, the flow units of the network edges must be assigned to the individual vehicles of the fleet. Additionally, the refueling stops of the hydrogen buses are scheduled. The process is called flow decomposition [KMS06]. In this step, we integrate the specific requirements of hydrogen bus fleets. The hydrogen refueling demand for every bus in the fleet and the production quantity of the electrolyser are added to model the refueling process. To reduce the investment costs for the electrolyser, the objective of the scheduling strategy is to minimize the peak hydrogen consumption while satisfying the result of the flow calculations modeled in Section 3.1:

$$\min z \tag{6}$$

$$s.t. \sum_{j|e_{ij}\in E} y_{ijb} - \sum_{k|e_{ki}\in E} y_{kib} = 0 \quad \forall\,(i,b)\in V\times B \tag{7}$$

$$\sum_{b\in B} y_{ijb} = x_{ij} \quad \forall\,(i,j)|e_{ij}\in E \tag{8}$$

The production capacity of the electrolyser within 24 hours for t in one-minute resolution is given by:

$$\sum_{t-1440}^{t}\sum_{b\in B} h_{bt} \le z\,\forall\, t\in T \tag{9}$$

The minimum and maximum refueling capacity for each bus per time step is given by:

$$H^{min} \le h_{bt} \le H^{max} \quad \forall\,(t,b)\in T\times B|\beta_{bt}=1 \tag{10}$$

$$h_{bt} = 0 \quad \forall\,(t,b)\in T\times B|\beta_{bt}=0 \tag{11}$$

To ensure that a bus can only refuel when it is parked in the depot, α_{bt} indicates whether the bus is in the depot at t (start of refueling) as well as at $t+T^f$ (end of refueling). The variable α_{bt} is set to one if the edge e_{ij} over which bus b moves at time t belongs to the set of depot waiting edges E^d. Otherwise, α_{bt} is set to zero:

$$\alpha_{bt} \ge \beta_{bt} \quad \forall\,(t,b)\in T\times B \tag{12}$$

$$\alpha_{b(t+T^f)} \ge \beta_{bt} \quad \forall\,(t,b)\in T\times B \tag{13}$$

$$\alpha_{bt} = y_{ijb} \quad \forall\, b\in B \quad \forall\,((i,j)|t_i\le t\le t_j, e_{ij}\in E^d) \tag{14}$$

$$\alpha_{bt} = 0 \quad \forall\, b\in B \quad \forall\,((i,j)|t_i\le t\le t_j, e_{ij}\in E\setminus E^d) \tag{15}$$

The hydrogen level of each bus is in the interval $[0, H_{max}]$ as described in Equation (16). The filling level is the sum of the initial filling level h_{bt0}, plus the hydrogen filled up to this point in time, minus the hydrogen consumed up to time step t as described in Equation (17):

$$h_{bt_0} + \sum_{t \in T \mid t > t_0} h_{bt} - \sum_{(i,j) \mid t_j > t_0, e_{ij} \in E} y_{ijb} D_{ij} H^d \geq 0 \qquad \forall\, b \in B \tag{16}$$

$$h_{bt_0} + \sum_{t \in T \mid t > t_0} h_{bt} - \sum_{(i,j) \mid t_j > t_0, e_{ij} \in E} y_{ijb} D_{ij} H^d \leq H^{max} \qquad \forall\, b \in B \tag{17}$$

$$h_{bt_0}, h_{bt} \geq 0 \tag{18}$$

The following variables are binary:

$$x_{ij}, y_{ijb}, \beta_{bt}, \alpha_{bt} \in \{0, 1\} \tag{19}$$

4 A Hydrogen Bus Fleet for Karlsruhe

To demonstrate the functionality of the proposed model, we investigate the operation of a hydrogen bus fleet in Karlsruhe, Germany. For this, we obtain data from three sources: Scheduled bus timetables from the 'General Transit Feed Specifications' archive of the municipal transport authority [Ka20a], distances for bus trips along the scheduled routes from the 'TRIAS' interface for electronic timetable information [Ka20b][7] and bus driving distances as well as the distance to the refueling depot that are calculated using the 'OpenStreetMap' software [HW08]. As the bus schedule is repeated weekly, we investigate the operation over a one-week period.

4.1 Implementation

We examine a section of the Karlsruhe travel authority's network in a radius of three kilometers around the Karlsruhe city center. For this purpose, the trips of the lines starting or ending in the respective radius are selected from the data of all lines. In a second step, we use a subsample of eleven bus lines that are served by 24 buses starting or ending in a 3 km radius around the city center to demonstrate the operation and scheduling of the bus fleet as proposed in 3.2. An overview of the number of lines and timetabled trips within the 3 km radius and the subsample is given in Table 2. For the specification of the hydrogen buses and the refueling process, we assume a maximum fuel capacity H^{max} of 40kg [HK18], a refueling time T^f of 10 minutes [SVS13], a fuel consumption H^d of $0.5 \cdot 10^{-2} kg/km$ [HK18] and an average driving velocity $\overline{V}^e$ of $50 km/h$ for the trips back to the depot.

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[7] We would like to thank the Karlsruhe travel authority (KVV) for the provision of the data regarding bus schedules and distances. The KVV is neither responsible, nor liable for the content of this paper.

Radius	Number of bus lines	Bus routes per week	Required number of buses
3 km	58	14,447	74
Sample	11	4,186	24

Tab. 2: Flow optimization for the bus transport network

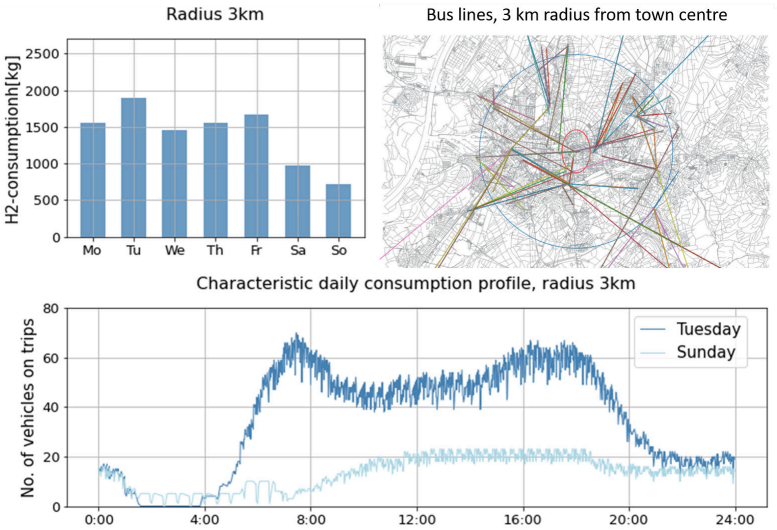

Abb. 2: Trip profiles and hydrogen consumption for a fleet of 24 buses

4.2 Results

In the given schedules of the sample of eleven bus lines, the number of required trips varies both within days and in-between days. For example, there are more bus trips on weekdays than on weekends. Besides, there are more trips during main commuting times and fewer trips at night. Exemplary trip profiles for Tuesday and Sunday are displayed in Figure 2. Uncontrolled refueling, i.e. refueling all buses upon return to the depot at the end of the day, leads to high peaks in hydrogen demand. With no optimized vehicle scheduling, this results in a maximum daily consumption of 639 kg of hydrogen, which causes the need of an electrolyser with a hydrogen production capacity of 1.5 MW. The optimized schedule aims to reduce such peaks. The flow decomposition returns the operation schedule for each of the 24 buses that are used on the eleven bus lines. The resulting trip distance and refueling events of an exemplary bus are depicted in Figure 3. The upper graph shows the distance travelled over time. Horizontal curve sections indicate the time spent waiting on an edge or in the depot. The refueling events for the bus determined in the optimisation are displayed as red vertical lines. The lower diagram in Figure 3 shows the bus' hydrogen storage level over time. For the entire fleet, the individual trip distances and depot waiting times are displayed

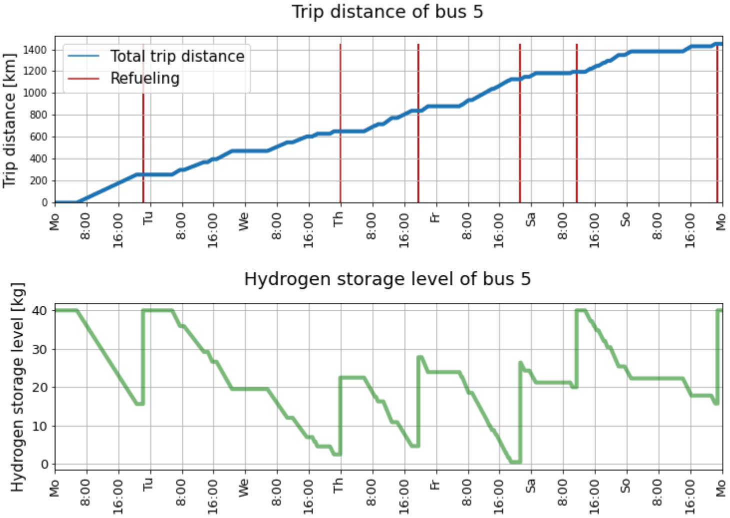

Abb. 3: Trip distance and refueling of a single bus in the fleet

in Figure 4. As the optimization is focused on an even operation of the bus depot fuel station and not on an even workload of the bus fleet, the workload distribution between all buses varies greatly. With the optimization presented in this paper, the maximum consumption within a 24 hour period is 510 kg hydrogen. This is 20% below the benchmark (639 kg). Assuming an electricity consumption of 58 kWh per kg of hydrogen produced by electrolysis [Re17] and 24 hours of production, an electrolyser with a capacity of 1.2 MW is required to produce 510 kg of hydrogen per day. For a maximum daily demand of 639 kg in the benchmark scenario, a 1.5 MW electrolyser is required. With investment costs of 1100 € per kW installed capacity for electrolysis [Bö20], the investment costs are 1,700,000 € in the benchmark scenario and 1,300,000 € in our optimized scenario. For the bus fleet with 24 vehicles, the investment costs for the purchase of an electrolyser can therefore be reduced by 400,000 €.

5 Discussion

The paper describes how a two-step approach of flow optimization and flow decomposition can be used to adapt the scheduling of hydrogen-powered public transport to the requirements of hydrogen supply by on-site electrolysis. In the first step, the flow optimization is described as a procedure that allows an estimation of the daily hydrogen consumption for fleets of different sizes. In the present work, a fleet of 24 buses is considered. The procedure is considered suitable for the application to larger fleets. In the second step, a problem formulation for flow decomposition is set up and the optimization with respect to smoothing

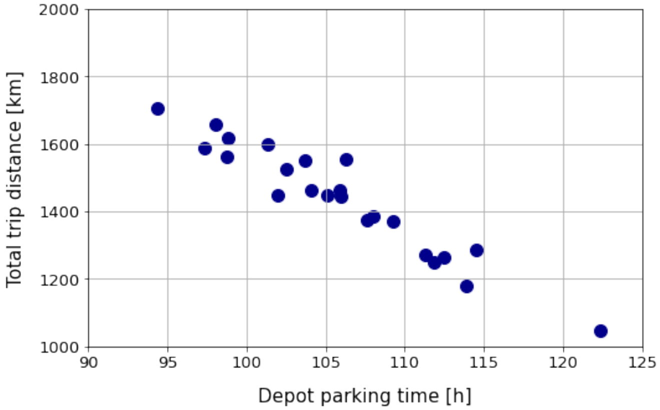

Abb. 4: Depot parking duration and traveling distances for each bus

the load at the filling station is performed. The results show that the required electrolysis capacity and thus the investment costs for the electrolyser can be reduced by 20% compared to a naive strategy. It is possible to analyse, if additional cost reductions can be achieved if the electrolyser is operated dynamically, making use of cheaper electricity at certain times. This could be done via time-of-use tariffs [Gu19] or, in combination with appropriate price forecasting [Sc20], via real-time-pricing tariffs. Further applications of on-site electrolysis could be in the context of local energy communities as a method to utilize locally generated renewable electricity [GHS20]. On-site electrolysis could furthermore be combined with centralized electrolysis and hydrogen delivery to fuel stations [Sc21]. For the decision to transit to hydrogen-based public transport, investment costs for hydrogen buses need to be considered as well. Currently in the range of 500,000 € to 625,000 € per bus, the investment costs are expected to drop to 400,000 € by 2030 [Be15].

6 Conclusion

The vehicle scheduling and operation strategy for a hydrogen bus fleet with on-site electrolysis proposed in this paper can support planning and investment decisions in public transport. We demonstrate how the approach can be used to reduce the required capacity of an electrolyser, lowering investment costs by 20% for an exemplary application in the German city of Karlsruhe. With this paper, we aim to contribute to reducing carbon emissions in the mobility sector by promoting the deployment of hydrogen-fueled public transport bus fleets and to enable locally emission free public transport.

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