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Evaluation of different scenarios to switch the whole regional bus fleet of an Italian Alpine region to zero-emission buses

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Summary

The South Tyrolean Transport Agency (STA) is evaluating the possibilities of converting several hundred buses to zero emissions in the coming years. The terrain of this Alpine region and the local temperature range implies challenging conditions for the applied technology. Bus lines in South Tyrol cover up to 55.2 km (one way) and differences in altitude of up to 1786 hm. Outdoor temperatures can range from -25°C on cold winter days to 40°C on hot summer days. In order to assess the possibilities and limits for replacing current diesel buses, the application of battery electric buses (BEBs) and hydrogen fuel cell electric buses (FCBs) were evaluated by Eurac Research.

Keywords: BEV (battery electric vehicle), fuell cell vehicle, bus, energy consumption, simulation

1 Introduction

1.1 Motivations

South Tyrol is the most northern Province of Italy and fully located in the Dolomite Alps. Next to its around 530.000 inhabitants [1]it is visited by several million tourists per year. In order to act as a representative region for green transport [2] and in consideration of the climate policy developments in Europe, South Tyrol defined a provincial climate plan [3], which includes reducing transport emissions. Within this framework, S.T.A (Strutture Trasporto Alto Adige) commissioned Eurac Research to evaluate the possibility of switching the current fleet of diesel buses with zero emission buses (ZEBs). An analysis of the ZEBs state of the art, South Tyrolean bus lines, and their timetables was carried out. The goal of this study was to understand which technology - battery electric buses (BEBs) or fuel cell electric busses (FCBs) - fits for a particular line. The project has been carried out from October 2020 until February 2021, with single additional activities until May 2021. The objective was a preliminary study giving first inputs on the request with ev. further specific studies to follow. The authors adopted a simplified modelling methodology accepting certain model limitations.

1.2 Study's structure

The study is structured as follows:

1. Market analysis of available zero emission busses (ZEBs);
2. Processing of a digital road network, including intercity bus lines;
3. Time tables' data collection and their integration into the network;
4. Energy consumption evaluation line by line for the two bus typologies (BEBs and FCBs) considering three charging scenarios;
5. Localization of recharging infrastructure.

2 Methodology

2.1 Vehicle Study

The ZEBs state of the art was important in order to analyse their employment on the different lines in South Tyrol. Before proceeding to a data collection on the performances of the different models, the main ZEBs characteristics were identified.

41 models of ZEBs were analysed (of which 12 were FCBs), sold in European, American and Asian markets. Buses are classified into three categories, according to the Italian Ministerial Decree of 20 June 2003 [4]:

- class C1: vehicles built with areas designed primarily for standing passengers (normally employed in urban areas), with more than 22 passengers;
- class C2: vehicles designed primarily to carry seated passengers, designed so that standing passengers can also be transported in the aisle and/or designated area (normally employed in urban and suburban areas), ; with more than 22 passengers;
- class C3: vehicles constructed with areas designated for seated passengers only, also referred to as "Coach", with more than 22 passengers.

Given the goal of the project, which is to provide a study on the possibility of changing the current fleet of diesel buses, the class of interest is C3. Given the small number of BEBs-class C3 and the absence of FCBs-class C3 buses at the time of data collection, C2 and C1 classes were also considered.

2.1.1 Energy storage

The study considered both battery capacity in kWh (for BEBs and FCBs) , and hydrogen storage in kg (for FCBs). Although some manufacturers state that battery capacity depends on charging velocity, authors considered slow charging condition (typical in depot) for data uniformity issues and did not include the aging process. Most of the data were derived from the manufacturer's websites.

2.1.2 Autonomy

It represents the maximum distance that the bus can cover in km. This parameter is influenced by the battery capacity, the HVAC (Heating ventilation and air conditioning) system, the regenerative braking (recovery efficiency and braking style), the trips and the general driving style. Many manufactures did not refer to standardized duty cycles (some of them adopted S.O.R.T. cycles [5]) and did not specify the HVAC's influence on energy consumption. The data collected were mainly obtained from manufacturer's website, in some cases by emails received directly from the manufacturer's or by interpolations.

2.1.3 Motor power

Given the presence of wheel motors in some models, this parameter corresponds to the sum of all motor powers present in the power train. It is expressed in kW.

2.1.4 Specific consumption

It represents the average energy consumption to travel a distance and is expressed in kWh/(100 km) for BEBs and (kg of hydrogen)/(100 km) for FCBs. As for the autonomy, the specific consumption has been deduced from information received from the manufacturer (website or emails) or through interpolation. The HVAC system and the adoption of a specific running cycle have in many cases not been declared by the manufacturer.

2.1.5 Vehicle weight

This parameter is expressed in kg and was used in order to make considerations on the vehicle's potential energy, given the variations of altitude on the South Tyrolean bus lines.

2.2 Road Network

To define the network on which to simulate the vehicles, the following input data were used:

- 2D data of official road networks;
- Elevation information through Digital Terrain Model (DTM) with a resolution of 2.5x2.5 m;

The road network was converted into a 3D vector, combining 2D roads with DTMs using the GRASS GIS \`v.drape\` command [6]. However, the 3D roads were including several elevation points that were not correct due to road infrastructures: bridges, tunnels, underpasses, subways. The official road network contained the information on the infrastructure type for each line. Therefore, the authors proceeded in interpolating the elevation of the critical infrastructure using a linear interpolation

[7] with the road elevation before and after the infrastructure. An iterative linear interpolation was implemented and applied to the road network to recursively remove the road segments with a slope greater than 20%.

The bus lines time schedule was provided by STA using the General Transit Feed Specification (GTFS) format. The time schedule provided is covering the full year, however for the simulations the authors selected in agreement with STA one representative day. The bus line geometries extracted from the GTFS file were forced to follow the 3D roads network moving the bus line point to the closest 3D road point using the GeoPandas python package

[8]. Then, using Shapely [9], the authors characterized each line with the total distance (subdivided by distance up and down) and with the elevation difference (distinguished in up and down).

2.3 Vehicle modelling and assumptions

The authors analysed the bus schedule to count the number of times that the stops were longer than 10 minutes. On the overall bus service, only 46 stops were registered. Therefore, it has been decided to ignore the stops within the line and to consider as a potentially eligible chance to charge the bus only the stops from one course and the next with a stopping time above 10 minutes.

The energy required by the bus to travel each line was assessed by performing a global energy balance for BEBs and FCBs. The study aimed to assess the feasibility to move the current public transport system to a pure ZEBs system, therefore the analysis was conducted selecting conservative values and considering the worst conditions a bus could encounter. The energy balance was performed based on the following formula:

$$E_{tot} = E_{tot} + E_{up} - E_{down} \quad (1)$$

With E_{dist} being the energy required to move the bus in a horizontal direction; E_{up} and E_{down} are respectively the energy required by the bus to travel upwards and the energy that might be generated through the regenerative braking system travelling downwards. To assess the energy due to the distance under conservative conditions the following formula was applied:

$$E_{dist} = c * D_l/\eta_{clima} \quad (2)$$

With c being the specific consumption of the bus as specified by the bus model datasheet; the authors considered the kWh/km for the BEBs and the kgH2/km for the FCBs as declared by bus model data sheet; D_l is the distance in km of the single bus line; η_{clima} is the increased consumption per km due to the efficiency of the space conditioning system. For the BEBs as η_{clima} = 0.75 [10] [12] as the efficiency of the heating system was considered and for the FCBs a η_{clima} = 0.75 [10] as the efficiency of the cooling system (as for the heating system the use of the waste heat of the fuel cell has been considered).

The energy required to travel up and down is defined as:

$$E_{up} = g * \left(W_{bus} + W_{people}\right) * \Delta_{up}/(\eta_{up} * \eta_{clima}) \quad (3)$$

With g as the gravity force 9.81 m/s^2. W_{bus} is the weight in kg of the empty bus; W_{people} is the weight in kg of the bus users calculated as the number of places available on the bus multiplied by an average weight per person of 70 kg; $\boldsymbol{\Delta}_{up}$ is the elevation difference in m; while η_{up} is the efficiency from battery to wheel. There an efficiency of 0.85 [11] for the BEBs has been considered and 0.425 for the FCBs has been considered. The second is the result of 0.85 (battery to wheel) multiply by the efficiency of the fuel cell (FC) to convert the hydrogen to electricity which was considered to be 0.54; η_{clima} is the penalty to guarantee the comfort condition within the bus using 0.75 as in the previous formula.

The energy that might be generated through the regenerative braking system is assessed based on:

$$E_{down} = g * W_{bus} * \Delta_{down} * (\eta_{down} * \eta_{clima}) \quad (4)$$

As worst condition it has been assessed that the bus is full when going upwards and it is empty when going downwards (so max weight to be lifted up, and min possibility to recover energy travelling down), so as in the previous formula g is the gravity, W_{bus} is the weight of the empty bus, $\boldsymbol{\Delta}_{down}$ is the elevation difference, η_{down} is the efficiency from wheel to battery that was considered to be equal to 0.40 [13] for BEBs and FCB, and with η_{clima} of 0.75.

All BEBs in the simulation have an initial level of the battery (90%) / FCBs a level of tank of (100%), and have a lower limit in the use of the battery of 15% for the BEBs and of 5% for the FCBs. The simulation tool goes through the time schedule and for each line it checks if there is, in the initial/starting place, a bus, already available, with enough energy to complete the line, if yes, then the line will be assigned to the bus, if the bus that is available at the stop has not enough energy, it checks if the bus stays at the bus stop for more than 10 minutes, if yes, then it creates a recharging point, then it checks if the energy in the battery is enough to complete the line, if yes it assigns the line to the bus if not it is marked that marked that the bus is not available, it checks the next bus or creates a new one, see Figure 1.

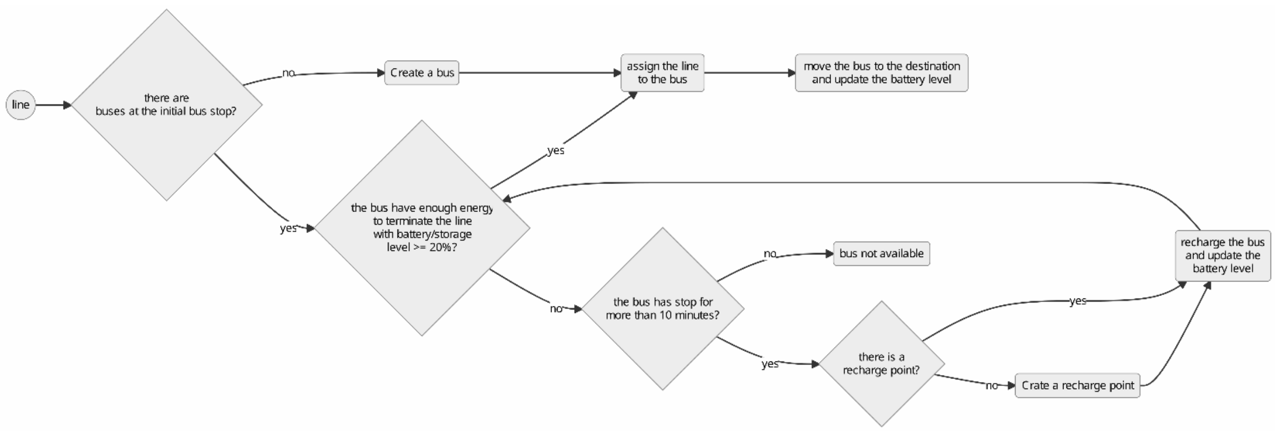

Figure 1: Flowchart with the battery and hydrogen storage system.

The simulation was executed under three different operative conditions. The first condition simulates the option to recharge the bus only during the night. The second condition simulates to recharge whenever the bus remains at the destination for a time longer than 10 minutes. The third condition follows the second one but reduces the recharge of the bus to the situation where battery/tank level is below 40%.

For the recharging of the battery / tank the following formula is used:

$$E_{recharge} = E_{flow} * T_{stop} * n_{recharge} \tag{5}$$

E_{flow} is considered to be 150 kWh/3600 seconds = 0.04167 kWh/s for the BEBs and of 0.075 kg/s for the FCBs as recharging / refuelling of the bus. This flow is multiplied by the number of seconds (rounded to the floor minutes) that the bus stays on the bus stop, multiplied by the recharge efficiency of the system (95% for the BEBs and 100% for the FCBs have been considered).

3 Results

3.1 Vehicle study

3.1.1 Energy storage

The range of the energy storage in the identified buses varied between 150 kWh and 650 kWh. For FCBs, determined battery capacities ranged between 40 kWh and 120 kWh while the hydrogen storage varied between 30 and 38 kg of hydrogen.

3.1.2 Autonomy

The autonomy of the identified busses varied between 200 and 370 km for BEBs and 300 and 400 km for FCBs.

3.1.3 Motor power

Motor power presented a range between 150 and 350 kW for both FCBs and BEBs, similar to the actual diesel bus fleet [14].

3.1.4 Specific consumption

Specific consumption ranged from 70 to 140 kWh/100km and 8.5 to 10 kg of hydrogen/100km for FCBs.

3.1.5 Vehicle weight

For BEBs, the weight ranged from 14000 kg to 27000 kg while for hydrogen buses, the only value accessible to the authors was 20000 kg.

3.2 Road Network

In the following the results of the analysis of the road network and the energy consumption by BEBs and FCBs in order to run the single bus line are shown.

Each line of the bus network has been characterized by the distance and the elevation difference, Figure *2* shows the scatterplot of the bus lines considering these two variables. As can be seen the maximum distance is less than 60km, while the maximum elevation difference is slightly above 1750m.

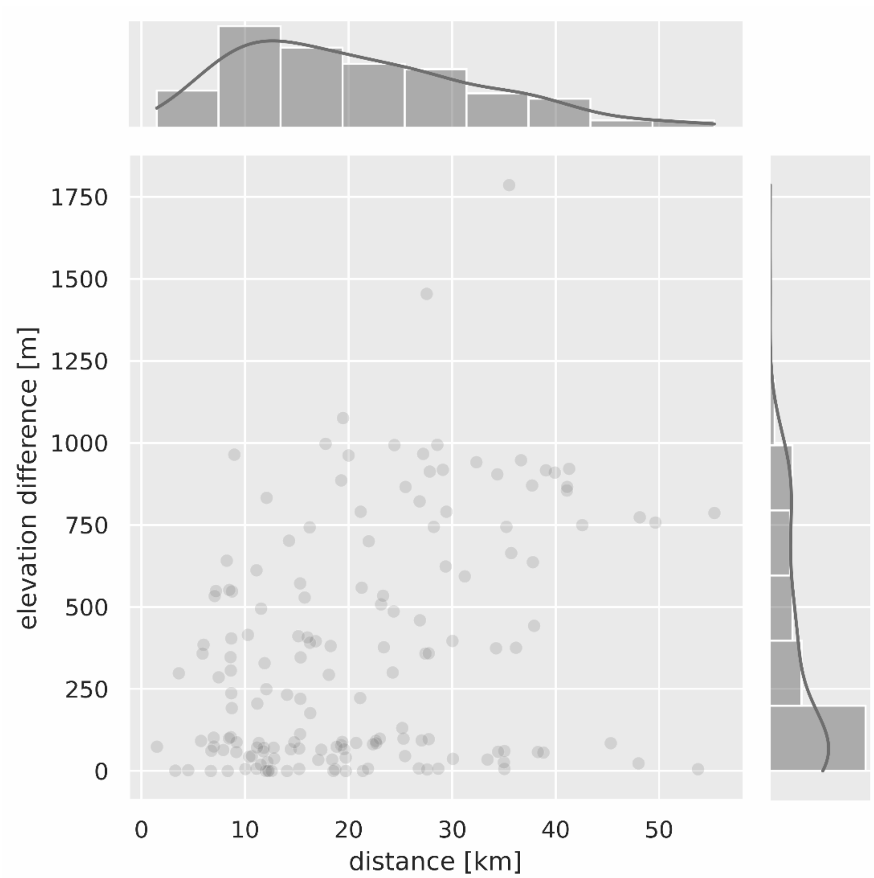

Figure 2: Statistical analysis of the network: elevation difference vs distance

Based on the formula described in the methodology section, the authors assessed the required energy of each line to guarantee the service under cautious conditions. Figure 3 shows the energy consumption of the round trip of one single line. As can be seen the majority of the lines can be served by bus types using batteries with limited capacity, while all the lines can be covered by buses with larger capacities available on the market. While for the FCBs all the bus lines can be covered by the tank capacity that are installed in the buses available on the market.

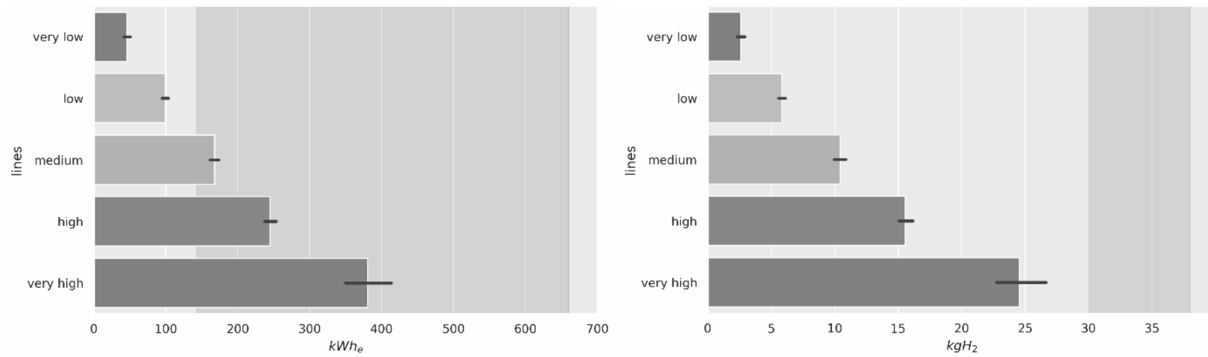

Figure 3: Energy required for each cluster of round-trip bus lines, the background grey colour shows on the left the battery capacity available on the market for BEBs and on the right the tank capacity available for the FCBs. The number of lines for each cluster is not equally distributed. In fact 9 lines are in the purple cluster, 17 in the blue cluster, 31 in the green cluster, and respectively 65 and 102 in the light green and the red cluster.

The average value of energy required for the line round trip is 139.8 kWh and 9.1 kg H2 for electric and fuel cell buses respectively, while the maximum energy demand is 508.9 kWh and 32.5 kg H_2.

3.3 Vehicle modelling and assumptions

As described in chapter 2.3 three different recharging options were simulated. Based on these assumptions it was defined how many buses [15][16] are required to guarantee the bus service for a full day, for a specific line, based on different recharging options. The single recharging options can have an impact on the number of buses needed and if only over night charging is allowed more buses are needed than if opportunity charging is allowed to. Figure 4 shows an example of state of charge considering the third simulation option, were opportunity charging is allowed if the battery level is below 40%. As can be seen the bus starts the journey with the battery level at 90% and is discharging during the day arriving several times at the final destination, around 14:00 the battery level goes below 40% limit and the stop was longer than 10 minutes, therefore the bus status is changed to recharge.

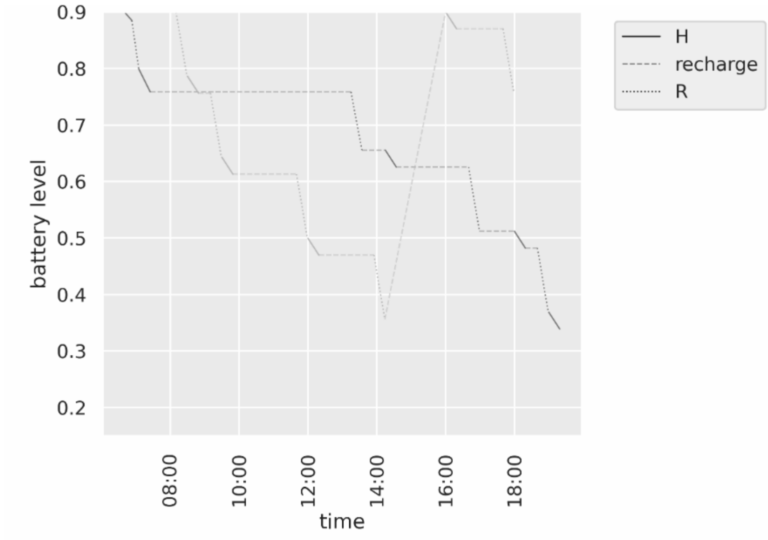

Figure 4: An example of the state of charge of a bus during the day travelling a specific line is shown. Each colour represents a bus, the different line styles represent the bus status: the continuous line is the bus that is going to his destination, the dot line is the bus that is on its way back to the origin, and dash line is the bus that is waiting and/or recharging.

The maximum energy required by the bus lines round trip is less than the maximum capacity of the batteries and tanks of the buses on the market. As shown in Figure 5, in both technologies, more than 78% of the lines can be covered with the same number of buses. In both technologies slightly more than 20% of the lines require more buses to guarantee the service. Al together around 6% more buses are required, independently of the technology chosen (BEBs of FCBs).

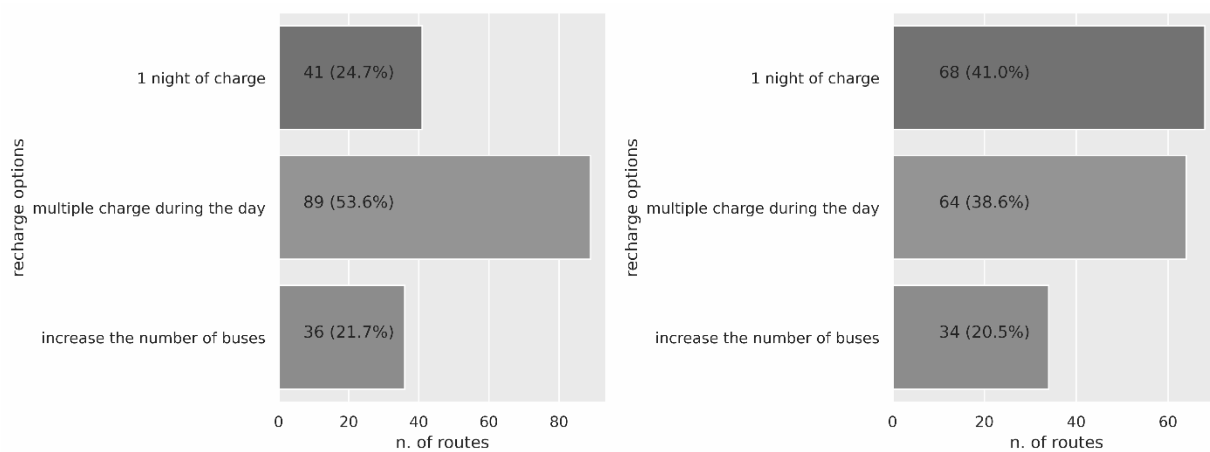

Figure 5: Number of lines that can be covered by BEBs (on the left) and FCBs (on the right) with a full recharge during the night, multiple recharge during the day, and by increasing the number of buses respect to the bus required by a diesel equivalent system.

The simulation tool also estimates the number of recharge stations and hydrogen refueling points required by the regional bus transport system. Following the used model for the BEBs the recharge infrastructure obtained is of 223 recharging stations assuming 150 kW of power capacity, while for the FCBs the required recharge stations are 206, which become 21 if the identified stations are aggregated and clustered using a radius distance of 15km.

4 Discussions and conclusions

This study evaluates the possibility to transfer inter-urban bus services in the Alpine region (South Tyrol – northern Italy) from diesel buses to battery electric buses (BEBs) or fuel cell electric buses (FCBs).

In order to do so, a model has been set up based on the vehicle's energy balance. Herewith the energy consumption is evaluated based on the physical characteristics of the single bus line (distance and altitude), climatic conditions and its time tables. As such the model can be implemented in mountainous areas and on intercity lines allowing the specific energy consumption.

An exhaustive work has been done to digitize all bus lines in South Tyrol by correcting more than 3 million points in the digital maps (tunnels, bridges, ..) . From the analyses carried out, the average distance of the lines is 17 km (max: 55 km) with an average height difference of 300 hm (max: 1786 hm).

Each line (distance and height difference) was transformed into energy consumed for the specific technology. The average energy required for the outward and return of the buses on the lines is 139.8 kWh for BEBs and 9.1 kg H_2 for FCBs with maximum consumption of 508.9 kWh and 32.5 kg H_2 respectively.

The very conservative calculation (assuming full bus upwards, empty bus downwards and difficult climatic conditions) results in a consumption of 380 kWh/100km for BEBs and 25 kg/100km for FCBs.

It is important to point out that as no data on the actual operation of the vehicles were available at the moment of the study, it was assumed that each vehicle is "dedicated" to one single line only.

Considering the buses available on the market and the calculated specific energy consumption, it appears that with both electric buses (higher performance models) and fuel cell buses 100% of the lines can be completed in a single round trip. Considering the schedule of a typical day and also allowing the electric buses to be partially recharged at stop times of more than 10 minutes, it turns out that for both technologies around 80% of the time one diesel bus can be replaced by one electric/fuel cell bus. For the remaining 20%, an increase of 6% in the number of available buses is necessary to guarantee the same time schedule. However, it should be borne in mind that:

- The estimate of energy consumption is precautionary.
- Technological progress is gradually increasing the autonomy of electric and hydrogen vehicles.
- This implies that the increase in the number of buses could be lower.

The results of the study show, however, that there is no clear difference in the distance covered in mountainous areas by fuel cell buses versus electric buses, but that both technologies can cover similar distances.

The clustering of recharge stations substantially reduces the number of stations required by the regional transport system. In the case of hydrogen and considering a clustering radius of 15 km, the number drops from over 200 to 21 refueling stations. This approach can also be applied to the location of electric charging stations.

With regard to the specific energy consumption / 100 km it was noted from the beginning of the project that monitoring data on the specific lines under all conditions (winter/summer, bus loaded/unloaded) are needed in order to validate the presented assumptions and to enhance the models results. Such data at that time were not available. Since some weeks preliminary monitoring data from the LifeAlps project [17] from the year 2021 for 15 buses being in service in South Tyrol on specific lines are available. A direct comparison of the data sets is not possible, but the preliminary results show an average consumption which is 50% lower than the one resulting from the simulations under conservative assumptions for both technologies - battery electric and fuel cell electric buses. Detailed evaluations on this dataset will follow in future publications.

If further data will confirm a lower average and max consumption it suggests that a technology shift to zero emission busses should be even less complicated with fewer charging stations / refueling stations needed and less lines asking for more ZEB buses than diesel buses actually in service.

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