Renewable and Sustainable Energy Reviews 165 (2022) 112555

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Electric-bus routes in hilly urban areas: Overview and challenges

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ARTICLE INFO

Keywords:
Electric bus
Benchmark route
Batteries
Charging
Hilly topography
Urban transportation

ABSTRACT

The electrification of public transport in cities is expanding, and fully electric buses (EBs) show great promise because of their high energy efficiency. We present the state of the art for electric-bus-related technologies, taking a closer look at the influence of the route's topography and the climate on battery demands. Included is a brief overview of the EB routes in Europe, which reveals a lack of very demanding benchmark routes, where new technologies from the perspective of seamless driving in difficult conditions could be tested. The trial EB routes set up in many cities allow testing under a variety of driving conditions; however, there is still a need for benchmark routes located in challenging environments with some demanding sections. We suggest a new, demanding, hilly benchmark route that provides the means for a technical evaluation of urban-transport electrification in a geographically specific area with particularly challenging driving conditions.

1. Introduction

The transition to electric vehicles (EVs) is one of the most important challenges of our time. Europe is striving to become a climate-neutral continent by 2050 [1]. Driven by environmental, climatic, economic, demographic, and social pressures, building sustainable, green, efficient and low-impact mobility solutions has become one of Europe's main priorities [2,3] and is central to several European projects, such as STEVE [4], ASSURED [5] and ZeEUS [6]. While all-electric drivetrains and hybrid cars have matured market-ready technologies, appropriate energy-storage technologies (high-capacity batteries) and a rapid-charging infrastructure [7,8] are currently research topics of great interest. The challenges and solutions to the problems associated with the sustainable development of energy-storage systems for the next generation of EVs are widely discussed in the open literature and several review articles are available, e.g., Ref. [9]. As research in the field advances, and better battery and rapid-charging technologies are developed, new challenges are emerging, including the difficulty of pairing rapid-charging equipment with an existing power-grid infrastructure [10] in terms of power transfer and drain, access and charging standards [11], as well as business models to support roll-out [12]. While privately owned (i.e., consumer) EVs remain a significant market challenge, with different support approaches being tested, electric buses (EBs) offer a much more straightforward path for testing and subsequent adoption.

Many of the problems that plague EV roll-out (driving range, charging-infrastructure availability) do not apply in the same way to buses, as their daily ranges and routes are generally known, fixed and recurrent, allowing the strategic development of vehicles and routes to ensure maximum efficiency and robustness. Full EBs, in particular, show great promise thanks to their high energy efficiency and possible combinations with renewable solar, wind and other sustainable energy sources [13].

Arguably, EBs can satisfy the most common operational requirements, given the expected improvements in battery technology [14]. There are, for example, many research, technology, innovation and demonstration advances included in the European Green Vehicles Initiative [15]. Indeed, some electricity-based solutions for buses and their charging stations have already been implemented. Toshiba tested the Toshiba Medium-Sized Bus with the Wirelessly Rechargeable SCiB™ Lithium-Ion Battery [16], several companies offer retrofitting for existing buses to give them electric propulsion [17], while GreenPower reported that Canada has agreed to electrify its double-decker fleet by 2021 [18]. Activities aimed at the integration of electric mobility into Singapore's power system are reviewed in Ref. [19]. Improving road-transport performance using new types of non-conventional energy [20], will also have a positive impact on health due to the reduced levels of pollution and noise, particularly in urban environments, as already considered in studies of electric mobility in several countries [21]. When we discuss the situation in Europe, e.g., in Geneva, 1000 tonnes of CO2 have been saved thanks to EBs [22], while some routes in Gothenburg are reported to be quieter, with emission-free, passenger-friendly buses [23].

Since 2010, when the first EBs started to run in European cities, the

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https://doi.org/10.1016/j.rser.2022.112555
Received 11 November 2020; Received in revised form 18 February 2022; Accepted 7 May 2022
Available online 21 May 2022
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Nomenclature

CO2	carbon dioxide
DC	direct current
DEM	digital elevation model
EB	electric bus
EU	European Union
EV	electric vehicle
ISO/IEC	International Organization for Standardisation/ International Electrotechnical Commission
SOC	state of charge
UITP	International Association of Public Transport; in French: L'Union internationale des transports publics
UK	United Kingdom
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States
V2G	vehicle-to-grid

fleet has been increasing annually (see Fig. 1). Particularly noticeable is the increase in the last three years, a consequence of European strategies [10].

Planning the introduction of EB routes in an existing public-transport network needs careful consideration of the terrain and climatic conditions as well as the social specifics of the area. It is very beneficial to carry out the testing of EBs on demanding benchmark routes, where the efficiency of the batteries and the charging infrastructure can also be evaluated in difficult conditions.

In this paper we review the requirements for urban bus routes in a harsh, demanding environment installation. Our idea was to draw attention to the need for a well-thought-out selection of benchmark routes and to share our findings about the current situation and the specific requirements for testing on demanding roads that can importantly influence the selection. In addition, we suggest and discuss a new benchmark route in a geographical area with particularly demanding driving conditions, with many steep ascents and descents, and a variety of climatic conditions. Another contribution of this work is a comparison of the proposed new benchmark route with several existing routes all around Europe, which reveals the similarities and differences in terms of the complexity of their topography and climatic variability. In addition to geographical and topographical challenges, the newly proposed EB route is of particular interest for regional development as well as the general development of related solutions, since there are not many existing operating routes that are challenging enough for a thorough evaluation of battery performance, particularly in cases where the infrastructure cannot be much improved. From this point of view, our suggestions and analyses could be useful for interested stakeholders involved in further improvements to EB-related technical solutions.

The rest of the paper is organized as follows. Section 2 explains the motivation for this work and describes the problem. Section 3 presents an overview of the current state of the art, some related work, including EB availability, involved technologies, influence of the road characteristics and the climatic conditions on battery performance. Section 4 overviews some existing, representative EB city routes. The proposed, new, demanding benchmark EB route and its details are presented in Section 5, complemented by a comparison with other existing routes. Section 6 draws the relevant conclusions.

2. Motivation

Introducing EBs requires their extensive testing in various topographic and climatic environments provided by benchmark routes with high diversity. The main goal of our study is to review all the requirements that need to be addressed when a new, hilly, urban bus route is planned. Besides an overview of the current availability of EBs and state of the art for the involved technologies, an essential aspect that needs to be considered is the influence of route topography and climatic characteristics on seamless EB driving. To test innovative technologies for the storage and management of energy in public transport we need to combine a charging infrastructure with the EBs to achieve normal driving, service routes and comfort within medium-sized city centers and municipalities. The performance of EBs can be improved by integrating high-performance (high-capacity and fast-charging) batteries with a state-of-the-art charging infrastructure, and the advanced management of the battery and the vehicle's operation. The selection of an appropriate demanding benchmark route is important, since it provides a "playground" for the technical and economic evaluation of urban-transport electrification, even in geographically specific areas where particularly challenging driving conditions are expected. A demanding driving regime refers to urban bus routes characterized by very hilly terrain, especially slow traffic, and many more frequent stops than

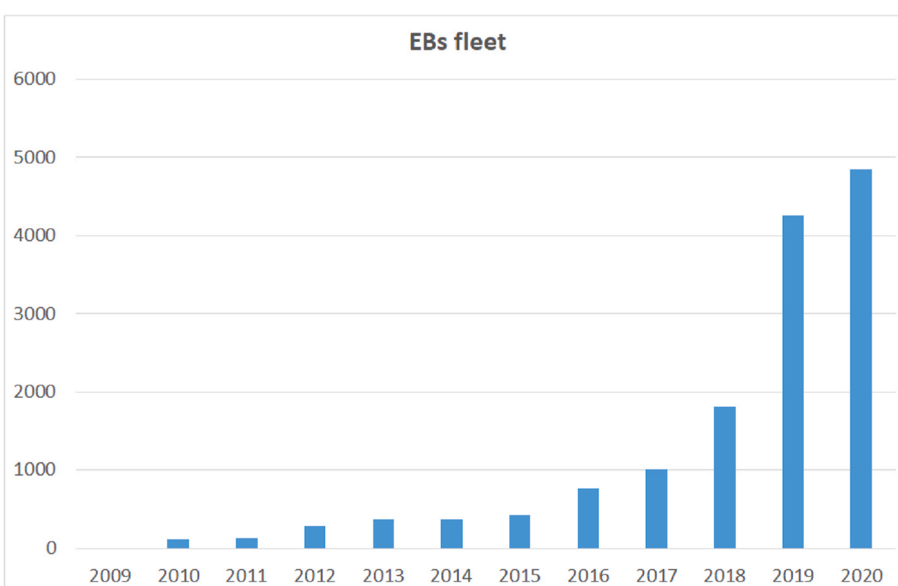

Fig. 1. Number of EB fleets in Europe until September 2020 [10].

typical city-bus passenger transport provides. These results can help to establish the basis for further research in the field, as well as accelerating the deployment of EVs and EBs.

We focused on the selection, review and merging of results from the literature on different evaluations and simulations to obtain an overview of the requirements that need to be addressed in connection with the testing of EB technologies. When integrating EBs into an existing public-transport network, the following points need to be addressed: selection of the existing bus routes to electrify, the electric-bus model, and the charging strategies with respect to the available or new charging infrastructure. This can be challenging to do in practice, due to the lack of readily available data describing the detailed driving profiles of each bus route. As an aid, various simplification models are often used [3], but the most useful information about the performance of EBs and their built-in batteries needs to come from suitable benchmark bus routes.

Most existing EB test routes are in major cities and urban centers or in areas where it is easy to provide a charging infrastructure. However, there are very few routes that have been set up with the main aim being to test the performance of EBs and innovative battery technologies under difficult conditions. Hence, we suggest a real-world, demanding, hilly benchmark route for the seamless driving and charging of EBs in urban transport. The aims and criteria for choosing the test roads include improving efficiency while reducing the pollution, CO2 footprint and noise.

This review highlights the benefits of introducing specific, demanding benchmark EB routes to the manufacturers of EBs, batteries and chargers, allowing them to test their products and obtain comparable results. We added the proposed, challenging route to the collected benchmark of real-world hilly routes described in the literature and made the first evaluation of its suitability for further testing.

3. State of the art and related work

3.1. Availability of electric buses

The EB market is growing rapidly, and many new technologies and solutions are being researched, developed and tested. While electric cars and electric trucks have been deployed for several years, there is now a greater focus on all-electric buses [24]. The process of implementing EBs is complex, in terms of technical, transport, economic and ecological issues, which all influence the choice of the bus-fleet exchange variant and scenario [25]. As reported in Ref. [26], there are many factors that affect transport agencies' decisions to go to larger-scale deployments; they also report some measures to overcome barriers and ensure agencies can transition to a new technology without affecting the transit service. The public acceptance of EBs also depends on their ability to provide dynamic passenger transport [27], with the need for the on-demand transport of passengers during low-utilization periods.

Trends toward the electrification of urban transport can be seen around the world [28]. On a global scale, China is a leading country in bus electrification, and this trend will continue for the next two decades [29–31]. The development and promotion of EBs in China even precede electric cars, due to the policy incentives. However, there are already seen some subsidy phase-outs and the increasing saturation of EBs in the cities, which will most certainly stabilize the EB market in China at a lower level than during the boom years of subsidy [29].

In Europe, the Netherlands is the fastest in developing its EBs fleets [32], followed by the UK, Austria, Spain, and Poland [10]. The development of EB fleets is also seen in Sweden [33], Latvia [34], Luxembourg [35], the countries involved in recent EU projects [6,7] and others.

The EB market in the USA is still in its nascent phase, with the presence of a few key manufacturers. The analysts foresee that the USA market will grow at 18.5% a year until 2024 [36]. Several fleets and transit agencies in the USA have shown a commitment to electrifying parts of their fleets of buses and shuttle buses. The cities with the largest EB fleets, New York City and Los Angeles, plan to transform all buses to electricity by 2040 and 2030, respectively [37].

Reports on the electrification of urban transport also come from many countries around the world, e.g., Japan [38], Malaysia [39], Australia [40] and many others. One of the recent EV outlooks [41] gives an overview of the development of EBs and discusses policies and strategies to deploy EBs and the charging infrastructure around the world, and even considers the potential impacts of COVID-19. Through the included case studies on the use of city EBs in different regions/environments this review highlights the specificity of different public-transport systems, the introduction of EBs facing specific network size challenges, supply infrastructure, the degree of privatization of the sector and the availability of non-ticket funding flows.

This review focuses on the current situation in Europe. Sustainable Buses [42] reports that in Europe 12% of the city buses registered in 2019 were EBs, and forecasts that approximately 40% of the new city buses will be electric in 2025. According to the latest data [10], the leading EU countries in terms of fleet size and the number of new EBs are shown in Fig. 2. This is also in line with the previous expectations of The Green Car Congress [43] that the Campaign for Cleaner Transport in Europe foresees an increase in the number of EBs on European roads.

The EB market is expected to grow significantly in the near future [44]. However, without the appropriate energy-storage and charging systems many barriers to adoption will remain: limited range, high operating weight, high purchase costs, lack of a necessary charging infrastructure, and additional downtime due to the charging or replacing of batteries. According to the AECOM Energy Storage Study [45], the role of energy storage is becoming crucial with the increasing levels of renewable (and intermittent) energy generation from solar and wind. In Ref. [46] an analysis of the EB distribution based on their curb mass, top speed, driving power, all-electric range and energy consumption is presented.

3.2. Involved technologies

When testing EBs against a benchmark, we also need to evaluate the assembly of the EBs with high-capacity, rechargeable batteries, while also considering the urban planning of charging-station locations, which offer a holistic solution for EB integration without compromising the vehicle's performance, comfort, or the safety of the driver and passengers.

The state-of-the-art batteries installed in EBs and the charging stations, combined with intelligent management, should allow a high level of self-consumption and demand-response under stable and secure conditions. Also, these high-capacity batteries will give the vehicles sufficient acceleration and hill-climbing ability, which is not yet fully available in commercial systems.

The whole system should consist of EBs and charging stations that derive their energy from renewable resources and the grid. Both the buses and the charging stations have energy-storage capacities and should be capable of both receiving and offering energy. When properly integrated, these systems can offer both demand and consumption smoothing, which is necessary to absorb the capacity peaks created by renewable energy sources, as well as the demand peaks created by local charging needs and regional events (such as extreme weather conditions). When connected to the regional electricity grid, the demand-response problems are alleviated, and the flexibility is increased.

As a standard procedure, any EB has to pass several standardized testing rules, that also consider temperature ranges for battery operations. These tests (e.g. Refs. [47,48]) define the extreme temperatures, under which the battery or other electrical equipment has to work safely, but tests do not define the long-term performance of the battery or the overall EB system itself. Therefore, the need for a benchmark route that also evaluates the performance and comfort of driving is needed.

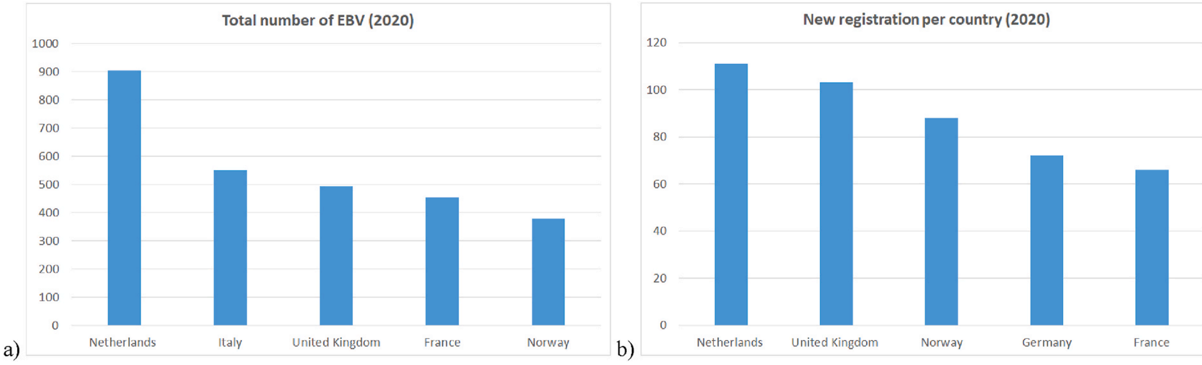

Fig. 2. Number of EBs in 2020 [10]: a) the total number per country, b) the number of new buses.

3.2.1. Electric batteries

In general, EBs have neither a continuous power supply (unlike electric trolleybuses, which have an overhead connection to mains power, EBs use on-board batteries) nor do they generate electricity on-board. As the energy density of batteries is low compared to diesel or hydrogen, the driving range of EBs is limited, and the charging process is time consuming [49]; they also suffer from "peak-load" problems, exhibiting unacceptable performance when climbing hills. To overcome these critical barriers to adoption, research has been focusing on the development of high-capacity batteries that are able to recharge quickly at ultra-fast charging stations. High-capacity batteries integrated into EBs that provide the required rapid charging and the expected vehicle performance, like good acceleration and hill-climbing ability should be adapted for increased safety, excellent cycle life, a good, useable SOC, effective regeneration, and the highest dynamic charge acceptance, promising a low total cost of ownership and better power reliability. A review presented by Ref. [9] summarizes the challenges facing the sustainable development of energy-storage systems in next-generation EV applications. The lithium-ion (Li-ion) battery is considered to be one of the most suitable batteries for EV applications due to its light weight and high power density. However, negative effects on health, safety, recycling and refurbishing still remain to be fully addressed. Hannan et al. [50] presented issues and recommendations for the energy management of Li-ion batteries in EV applications. Additional challenges include the degradation of Li-ion batteries and travel needs with vehicle powertrain models, which were analyzed in Ref. [51] with a V2G-Sim simulator [52]. In Ref. [53] it was shown that the SOC estimation and state-of-health monitoring are the key indicators to determine the degradation level of the batteries. The relationship between the battery technologies and the EB's performance as well as the strengths and weaknesses of different batteries and charging technologies implemented in the European projects are discussed in Ref. [54].

New energy-storage systems are being tested and deployed in EVs [55] and are providing increased flexibility in meeting the challenges of EVs [56]. As on-board energy systems improve, they need to be tested thoroughly and demonstrated widely to ensure proper and timely adoption and deployment.

3.2.2. Rapid-charging systems

With a rapid charging method electric-car batteries are charged with DC, at 50 kW or more. Currently, the state of the art is ultra-rapid DC chargers, which typically supply power at 150 kW or more, with some being capable of up to 350 kW. The estimated charging time is 10–45 min, depending on the vehicle type and needs.

The design of a rapid-charging-station infrastructure is crucial for the successful integration of EBs into a demanding, hilly environment. A detailed review of state-of-the-art EV chargers is presented in Ref. [57]. The locations of individual charging stations (e.g., pantographs [58,59]) depend on many factors, such as existing bus routes, terrain configuration, distances to other charging stations, distances to existing solar-panel installations, distances to grid connections, available space, public acceptance, regulations and standards. As explained in Ref. [60], the installation of rapid-charging facilities reduces the overall cost of operating an EB route.

The rapid-charging systems currently available on the market are based on the coupling technologies described in the OPPCharge documents [61] and the related ISO/IEC standards. The technology (used by Volvo) is also discussed by Ertico and their partners [62], an industrial producer of electric buses [63] and a producer of charging stations [64]. UITP [65] has initiated discussions on this topic, bringing industry together and disseminating the results to the appropriate channels (the European Committee for Standardisation and the European Committee for Electrotechnical Standardisation).

Like EBs, the charging stations should also use state-of-the-art batteries that can withstand very rapid charging and discharging rates (i.e., a full charge in just 10 s [66]). Charging EV batteries directly from the grid would require high-power connections, would create large demand peaks during charging, and could destabilize the grid (see the next section). This should be mitigated by batteries installed locally at charging stations. To improve the profitability of the rapid-charging stations, while decreasing the high energy demand from the grid, these stations might also include some renewable generation (e.g., wind and photovoltaic) and a storage system [67].

3.2.3. Integration of charging stations into the electricity grid

When building a charging infrastructure for powerful EBs we have to consider the problem of an efficient electrical energy-storage system [68] that will quickly distribute the required energy when the EBs arrive at the charging station and lessen the negative impact on the energy-transmission system as a whole.

The charging station supplies electrical energy to the batteries of the EVs and as such should be in line with the battery standards. These charging stations are on-street facilities provided by electric utility companies. The impacts of peak load during uncontrolled battery charging can be a serious problem, as it might have a destabilizing effect on the grid, and special attention must be paid to the proper integration of the charging stations into the grid [69]. Power transfer directly from the grid can be costly, and can also introduce disturbances; large power flows (in relation to the total energy capacity of the involved energy-storage systems) might also be harmful to the energy-storage systems.

The impact of the charging infrastructure and EV charging on the grid was presented in a comprehensive review [70], which also covers some important international EV charging and grid-interconnection standards.

An effective model-based tool for planning a rapid-charging battery-electric-bus system proposed by He et al. [71] considers not only the upfront costs for building a rapid-charging EB system, but also the potentially high operating costs from demand charges, determining in this way the best trade-off among charger cost, on-board battery cost, energy-storage cost, and demand-charge cost.

3.3. Urban planning of charging stations

Due to the complexity of locating the charging infrastructure for EBs, the problem has already brought some attention from the scientific community [72,73]. The challenge of placing EV charging stations at selected bus stops, to minimize the total installation cost of charging stations, is considered in Ref. [74]. In Ref. [72] a dynamic optimization model was developed, within a Stockholm case study, to establish a charging infrastructure for EBs. Like with the urban planning of charging stations, there are many challenges [75], provides a methodology for the cost-optimized planning of depot-charging EB fleets and their charging infrastructure. The planning of an EV charging infrastructure in cities with limited space was addressed in Ref. [73].

For the best design of the charging-station network, an appropriate decision-support model should be used to enable simulations and transparent analyses of alternative solutions for positioning charging stations along the routes of EBs. For this, a number of open-source tools for traffic simulations can be used, such as MATSim [76] (a framework for implementing large-scale, agent-based transport), MovSim [77] (an interactive, open-source traffic simulator focused on investigating the fundamental issues of traffic dynamics), and SUMO [78] (microscopic and continuous multi-modal traffic simulation package designed to handle large networks). There are also several commercial simulation tools with different properties, e.g., PTV Visum [79], dedicated to multi-modal transport planning.

Such tools can be further upgraded, like in Ref. [80], to the level of individual needs and as such it can be used as an evaluation tool for different scenarios in the design-optimization process for the positioning of charging stations in a benchmark route case, as well as for other cases.

3.4. Parameters influencing energy consumption

The evaluation of an EB's energy demands has become an important prerequisite for the planning and deployment of EB fleets, as well as for projecting the needs of the charging infrastructure. To assess the energy demands when operating EBs on a certain route, the significant parameters that can influence the power consumption of EBs, such as the route topology and the climatic conditions, should be taken into account.

As an example, the performance of an EB travelling on three different routes was analyzed in the city of Porto [81], where the main objective was to correlate the type of route on which a bus travels with the amount of energy it consumes. An experimental study of the charging behaviors of EBs based on the probability statistics method [82] analyzed the data sets collected for fleets of over 17,000 EBs operating in Chinese cities. The authors of [83] described a case study that includes a selection of test vehicles from different producers, a selection of indicators and a selection of routes to test the buses in one city. Gallet et al. presented a dynamic model to calculate the energy demand of an EB fleet in Singapore [84]. Specific consideration was given to hybrid systems, as in Ref. [85], where the authors analyzed the influence of different driving cycles on a hybrid energy-storage system, including the optimization of super-capacitor size and the energy-management strategy for EV use. This influences the battery requirements as well as the number and size of the necessary charging stations. Besides small energy consumption, an important aspect of an EB's driving is the ride comfort. In this context, a novel method for optimizing energy management and ride comfort in hybrid plug-in vehicles based on traffic signals and real road information described in Ref. [86] could be beneficial.

3.4.1. Influence of the route's gradients

Recent literature often discusses models and algorithms to predict the energy consumption of EVs and the importance of considering road-topography information, driving behavior, variation of the total mass of buses by loading the passengers, weather conditions and other specific parameters. In this context, several studies were carried out to evaluate the effect of the road slope on the EVs' energy consumption and energy recuperation processes. It is a well-known fact that energy consumption increases during periods of acceleration or ascent on uphill routes. Inversely, the energy consumption decreases on descending slopes or when the EB decelerates/brakes and the amount of recuperated energy increases. A review of some of these studies is summarized in the following paragraphs.

In [87] the authors studied the impact of road gradient on an EV's electricity consumption by combining long-term GPS tracking data with digital elevation model (DEM) data for roads in Aichi prefecture, Japan. They showed that a consideration of the road gradients significantly improves the prediction of energy consumption and should be considered in the model. Moreover, they showed that the effect of the road gradient on energy consumption becomes more distinct with steeper road gradients. A consideration of the gradient parameter improves the estimation accuracy of the electricity consumption by up to 8%. The increase in consumption is thus greater than the impact of fixed effects in driving patterns among various EV drivers, which contribute about 2% to the model's accuracy. This result contributes toward an understanding of the challenges and benefits associated with downgrade braking on energy regeneration in the hilly regions.

Similar findings were discussed in Ref. [88] where the authors showed (based on the experimental results obtained for Lupo EL) how consideration of the route slope parameter in the model for calculation of energy consumption of a battery-electric vehicle improves prediction of energy consumption. The same trend in increasing the energy consumption can be expected for EBs as well.

Another research study with the goal of reducing the uncertainty regarding the EVs energy consumption [89] discusses a specific case of EBs. For validation purposes the authors used real-world data (i.e. dynamometer tests and coast-down measurements), which showed that their energy consumption model with neglected slope factors can accurately predict the consumed energy for the relatively flat routes in the Netherlands. However, they pointed out that the deviations caused by road-slope effects should not be neglected when the routes are not flat.

A recent paper [90] gives an even more detailed analysis of the impact of the road-slope factor on the energy consumption and energy-recuperation processes. The authors conducted real-word experiments through which they checked the extent of the impact of the road slopes of up to 8% and showed that the EV recovers more energy on downhill roads than on uphill roads, but the amount of recovered energy prevails only for negative slopes higher than 2%. For the uphill slopes higher than 8%, there is no recuperation anymore. As evident from Fig. 3 showing the experimental data presented in Ref. [90], the amount of the consumed energy on uphill roads is always significantly higher than the recuperated energy on the downhill roads with the same slope. Moreover, the experimental results indicate that energy consumption of EVs on the hilly roads is higher than on flat roads. In connection with this, ensuring/testing the battery regime providing the conditions for seamless driving of EBs can be more demanding in hilly city areas.

3.4.2. Influence of climatic conditions

Since in-vehicle equipment (e.g., air conditioning systems) can have a significant influence on battery performance, it is necessary to take climatic conditions into account to accurately estimate energy consumption.

The impact of weather conditions was discussed in a case study [91] where the authors investigated the situation of EBs in Baoding, China. In Ref. [92] the authors demonstrate how the ranges of electric vehicles depend on the in-cabin comfort and therefore on the prevailing local conditions, which depend on geographical location and the time of the day. A case study of EBs in Aachen [93] demonstrated the dependency of environmental impact on the EB's charging time, which varies with the

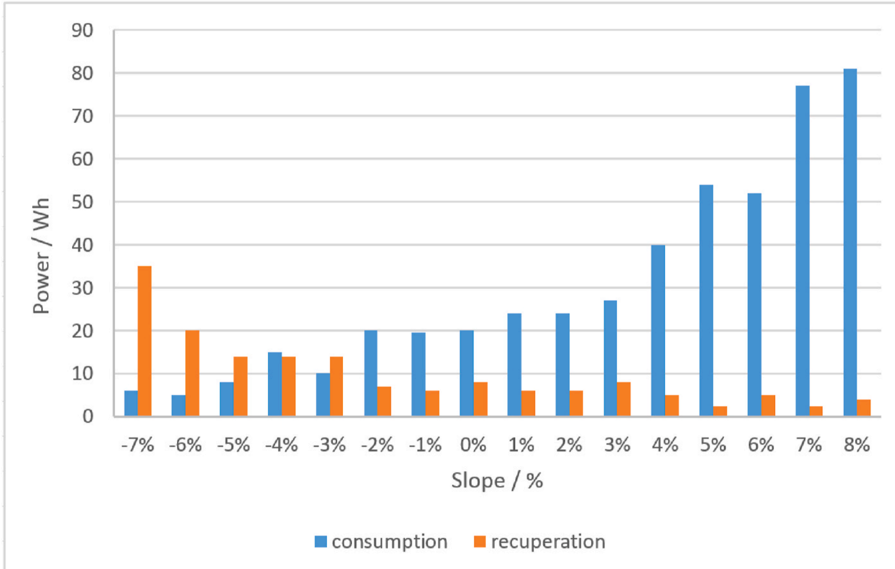

Fig. 3. Energy consumption and recuperation depending on route slope according to Ref. [90].

time of the day and the season. An experimental study in Helsinki [94] revealed the influence of temperature factors on the energy consumption of EBs. A simulation-based study of the impact of a heating system on the range of commercial EVs [95] showed that the range varied depending on the cabin's air-conditioning loads, and can be reduced by up to 30%.

A moderate level of power consumption by ancillary components is not critical for the battery. However, higher levels of ancillary power consumption and driving uphill will lead to the need for more frequent charging of the batteries and to greater infrastructure requirements. In order to maximize the comfort of the passengers, the cabins of EBs are air-conditioned, irrespective of the season. However, it should be noted that air conditioning requires significantly more energy during very low or very high outside temperatures. Power consumption is negligible only in the narrow temperature range from 10 to 20 °C [93], while temperatures below 0 °C and above 25 °C increase power consumption to 100%, as shown in Fig. 4.

It is also important to note that an extreme outdoor temperature could significantly impact on a battery's performance (e.g., the relative battery capacity at 0 °C is only 79% of the capacity at 25 °C [96]). From this point of view, low temperatures are even more demanding for batteries than high temperatures. Depending on the climate, batteries might be additionally burdened by air-conditioning devices most of the year. This is in agreement with the results of earlier studies aimed at EVs, e.g. Ref. [92], which showed that the energy consumption of the cabin's thermal comfort conditioning system is a function of the local temperature conditions, which vary geographically, diurnally and seasonally.

In [97] the authors analyzed the dependence of the EBs' energy consumption on the climatic and atmospheric conditions based on experimental data obtained for several EBs driving on relatively flat roads in the city of Cluj–Napoca in Romania. The experimental data collected over a period of 12 months showed that energy consumption is significantly higher during the winter and lower during the summer. Besides, the share of the recuperated energy (partially compensating for the consumed energy) is significantly lower in winter than in the summer months. The presented data showed the variance of energy consumption from about 1.0 kWh/km in summer time to up to 2.2 kWh/km in the winter time, while recuperation varied from 0.2 kWh/km in

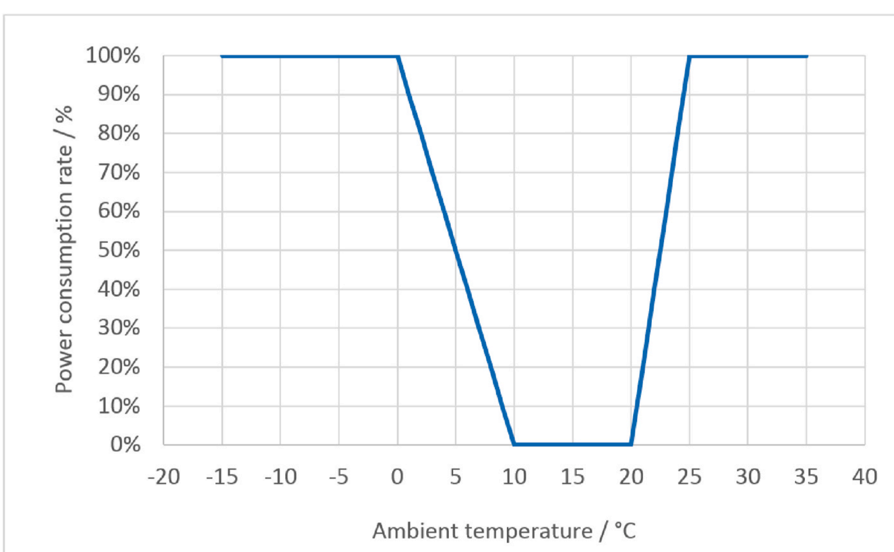

Fig. 4. Energy consumption rate of the air conditioner depending on the outside temperature [93].

winter time up to 0.6 kWh/km in the warmest summer months.

From the data presented in the paper we can conclude that the recovered energy in the winter time can be significantly lower than in the wormier months, when the consumption is lower (the consumption in January can be more than 60% higher than in July).

4. EB routes in Europe

An extensive overview of the operating routes for EBs in Europe [98] describes nearly 100 routes in 62 cities of 21 European countries. Depending on the terrain's topography, the report classifies routes into four main categories: flat (55), moderate (30), hilly (8) and mostly flat with moderate hilly regions (7). Some of these routes are presented with more details about their topography, climatic conditions and other relevant properties. The maps of the routes in Figs. 5–14 and 16 are drawn using Google Maps [99].

4.1. A need for benchmark routes

Topics in the related case studies and review articles touch on a variety aspects. However, the messages we receive from them indicate the importance of a proper choice of the bus routes or the consideration of city roads that can be appropriate for testing EBs. Studies are mainly focused on a specific situation, and the results are not easily extrapolated. Generally, the independent testing of EB performance is not included in these studies, or there are simply not many reports.

Most of the studies mentioned earlier consider situations specific to large and densely populated cities. In general, the selection of the bus routes to be electrified depends on existing bus routes and the configurations of the city streets. The most applicable locations for charging are at the major public-transport hubs and at depots. However, decisions related to setting up new test roads are not always straightforward. In general, it is important to consider the following aspects: (i) route characteristic and location (topology, climatic conditions, existing infrastructure), (ii) appropriateness of benchmark routes and roads selection (to collect meaningful input data for particular analyses), (iii) the number of bus stations, the number of passengers, the operating time (day or night), and the charging mode/time.

This information can be very different and depend on individual cases, so that the results of the tests cannot be easily compared. Accordingly, any independent, comparative testing of the performance of buses, batteries, etc. Is difficult. Simulations of specific use cases are very helpful; however, physical EB performance testing is still required by manufacturers.

4.2. Selection of exemplary routes

This section gives a review with short descriptions of ten selected exemplary EB routes traced in ten European cities. Our selection was based on the routes' diversity, including topography and climatic differences, as presented in various mobility-related project reports, e.g., Refs. [7,100–102].

The topography considers the profile of the route (as flat, moderate, hilly) and the climate considers the range of temperatures throughout the year. When selecting exemplary city routes, we carefully chose among the routes categorized as hilly, or at least with some hilly sections. Furthermore, we chose among cities in regions with climatic characteristics, which are especially demanding from the aspect of battery consumption due to the long and cold winters, or long periods in which batteries are additionally burdened with cabin air conditioning. Some of these routes are primarily aimed at the transportation of locals (e.g., Älvängen), others are also tourist-oriented (e.g., Cagliari). Many of these routes are also used for testing purposes (e.g., Hamburg). All the route characteristics are compared with our proposed benchmark route. Overall, the bus routes described in Ref. [98] are of different lengths (from 3.5 to 17.2 km, the longest is 50 km) and the EBs on these routes run 169 km a day on average (30–340 km). The EBs' average speeds are 12–40 km/h (most often 15–20 km/h). Exemplary routes are also visualized on maps to present their variability.

4.2.1. Älvängen, Sweden

The selected bus route in Älvängen is a 5-km circular route through the city center, on which the EB runs at half-hour intervals during peak hours, which match the schedule of the commuter trains [103]. There are 13 stops along the route, spaced at about 380 *m*, on average, fairly evenly throughout the city. The map of the route is presented in Fig. 5.

The topography of this route, with three moderate ascents and a cumulative altitude variation of 50 m (Fig. 15a), is categorized as hilly [98].

The EB on this route operates for 10 h a day. In the middle of the day, its battery is charged for a couple of hours to enable the afternoon tours. Rapid charging is available at the terminal and slow charging at the depot.

The climate in Älvängen is cold and temperate. The lowest temperatures fall to −5 °C, while the highest summer temperatures do not exceed 20 °C.

4.2.2. Budapest, Hungary

The selected EB route in Budapest is Line 39 [98], which is taken along a 3.4-km route on the hilly western Danube embankment of the city center. The route is circular and has 20 stops, which are 170 *m* apart, on average. A map of the route is presented in Fig. 6. As seen from the elevation profile of the route in Fig. 15b, there are several major ascents, and the total height difference is up to 180 *m*. The charging time at the depot varies from 1.5 to 5 h.

Budapest has a maritime climate, with cold winters and warm summers. During the winter, there is regular snowfall and the daily mean temperature is 1.5 °C. The long summer – lasting from May until mid-September – is warm or very warm. Heating or air conditioning is needed for most of the year.

4.2.3. Cagliari, Italy

The EB route in Cagliari, Line 5 [102], is a seafront road that connects the center of the city with the suburban region. It has two configurations: a shorter (18 km long) winter configuration and a 25-km summer configuration. A map of the route is presented in Fig. 7.

The route's topography is moderate with a maximum variation in altitude of 80 *m*. The longer summer configuration includes an additional 7-km flat section. Its elevation profile is presented in Fig. 15c.

The test Line 5 was designed to assess the feasibility of equipping trolleybuses with traction batteries in order to extend the advantages of

Fig. 5. Map of the route in Älvängen. (Maps Data: Google ©2022).

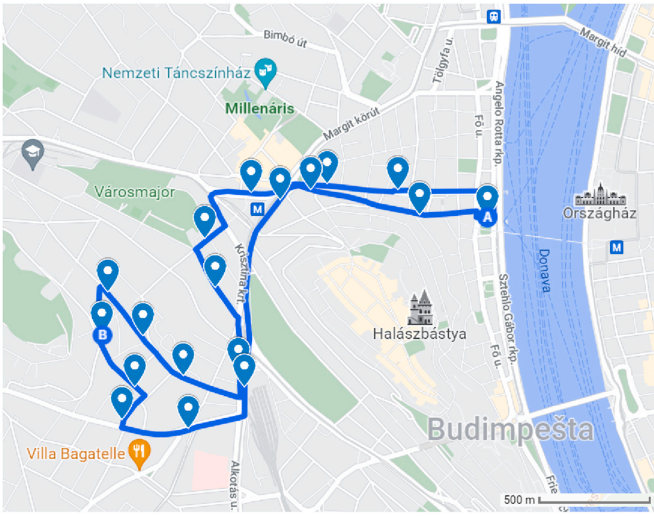

Fig. 6. Map of the route in Budapest. . (Maps Data: Google ©2022).

trolleybuses (less noise and air pollution, lower energy costs) with the flexibility of traditional buses. With properly designed vehicles and charging infrastructure, the "battery-trolleybuses" make it possible to extend the Cagliari public transport service without the need to install a new infrastructure.

The climate in Cagliari is warm and temperate. The average temperature ranges from about 10 °C in the winter period to about 25 °C in July and August. During the winter it is rarely very cold; however, the temperature can fall to zero or even a few degrees below. In the hottest summer days, the temperature can exceed 40 °C.

4.2.4. Eindhoven, The Netherlands

Since 2016, EBs have been operating on several routes in the city center and its surroundings. Their lengths range from 4.4 km to 12.3 km. The Dutch aim to make public transport pollution-free by 2025. All the routes have a flat topography. As a representative, Fig. 8 presents Line 401 [104]. The route's elevation profile is presented in Fig. 15d.

For the battery charging, rapid chargers (450 kW) are distributed over strategically located charging points, while the low-power chargers (30 kW) are available at the depot, where the buses are slowly recharged at night, so that they can start with a full battery and a preheated interior in the mornings [105].

In Eindhoven the climate is warm and temperate. The lowest temperatures are rarely below zero degrees. The maximum difference between the lowest and the hottest temperatures rarely exceeds 20°.

4.2.5. Gothenburg, Sweden

The EB runs on Line 55, which is an 8-km-long return route taken through the city center [106]. A map of the route is presented in Fig. 9. Its topography is moderate (the greater part of the route is through the flat valley of the river and one shorter section involves a moderate hill). The route's elevation profile is presented in Fig. 15e.

The charging infrastructure allows both the opportunity to charge

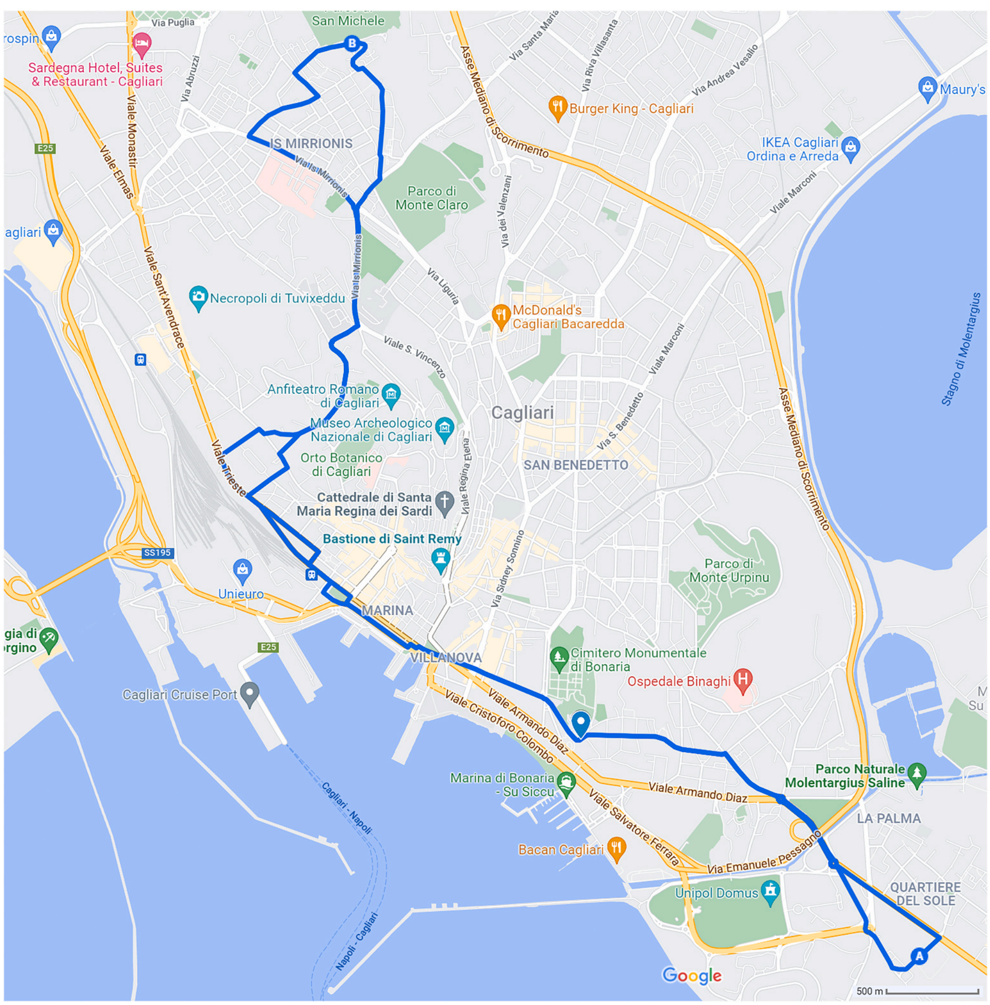

Fig. 7. Map of the route in Cagliari. (Maps Data: Google ©2022).

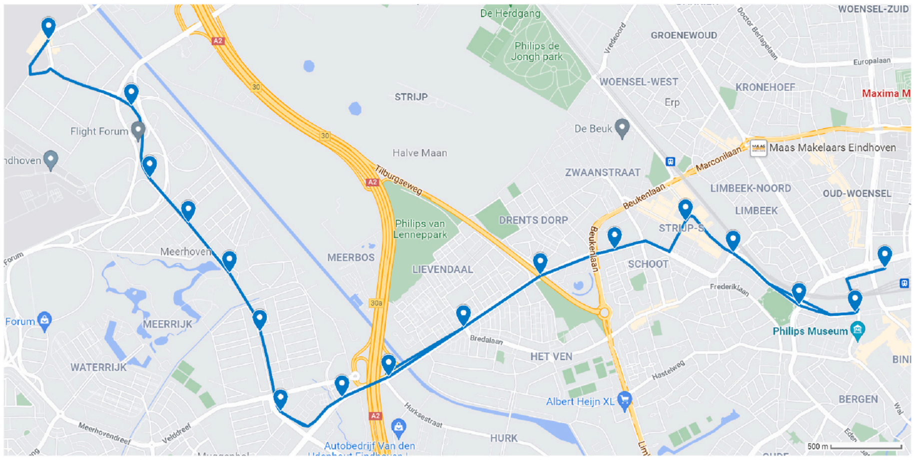

Fig. 8. Map of the route in Eindhoven. (Maps Data: Google ©2022).

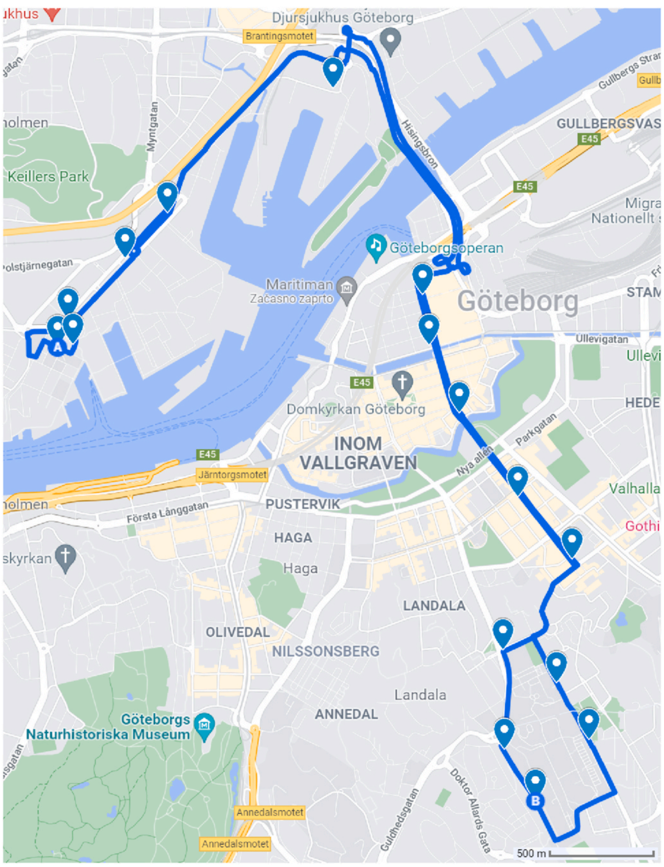

Fig. 9. Map of the route in Gothenburg. (Maps Data: Google ©2022).

using pantographs at the terminal, at selected stops (3–6 min), and overnight charging (the depot, for 4 h) [98].

Gothenburg has a maritime climate. Despite its northern latitude, summers are warm, with average high temperatures of around 20 °C, although temperatures of 25–30 °C do occur sometimes (which require the occasional use of air conditioning). Winters are cold, with temperatures of around 0 °C, though it rarely drops below −15 °C.

4.2.6. Hamburg, Germany

In the city center of Hamburg, a dedicated test route called "Innovationsline 109" [107] was set-up in the frame of HyER to test several new bus technologies. On this route, pure-battery EBs, as well as EBs with a fuel-cell range extender, have been tested since 2014. The aim is to tackle CO2 emissions and noise levels, and to bring more comfort to passengers as well as testing the advantages and disadvantages of different technologies in real-life conditions. The topography of this 9-km-long route is mostly flat. A map is presented in Fig. 10 and the elevation profile in Fig. 15f.

The batteries of the EBs are charged using pantographs at the terminal, and at selected bus stops for 8 min. Overnight charging takes place at the depot, for 3–6 h.

The climate in Hamburg is mild, and generally warm and temperate. The hottest month of the year is July, with an average temperature of 17 °C (max. 24 °C). The lowest average winter temperatures are below 0 °C, and they can drop down to a few degrees below zero.

4.2.7. Helsinki, Finland

EB Line 23 is 9 km long. It runs from Rautatientori, the main railway square in the Helsinki center, to the northern part Invalidisäätiö; it is also used for experimental testing [94,108,109]. The topography of the route is flat, even though the route has some variation in terms of elevation. As an illustration, see Fig. 15g.

An EB is charged during one end-stop event and 15 rapid-charging events per day (charging time less than 5 min [110]).

The climate in Helsinki is cold and temperate. The lowest winter temperature is −6 °C, while the maximum summer temperature is 17 °C, on average (and does not exceed 20 °C).

4.2.8. Osnabrück, Germany

The EB in Osnabrück has been in service since August 2013 [7]. It operates on the 3.7-km route in the city center with a flat topography. Every day it travels a distance of 148 km. A map of the route and its elevation profile are presented in Fig. 12 and Fig. 15h, respectively.

The charging infrastructure in Osnabrück allows charging at the rapid-charging stations at the terminal stops, as well as slow charging and balancing at the depot [7].

The climate in this region is warm [111]. The warmest month of the year is July, with an average temperature of 17 °C (15 °C–21 °C). The lowest average temperature in January is 1 °C, and rarely falls below zero degrees.

4.2.9. Östersund, Sweden

Line 6 in Östersund is a 14-km main bus route that runs from Torvalla, south of the city, through the city center and to the newly built Brittsbo district in the north. Part of the route has dedicated bus lanes. It began its operation in March 2018 and this route, with a mostly flat topography, is operated by three battery EBs. A map of the route and its elevation profile are presented in Fig. 13 and Fig. 15i, respectively.

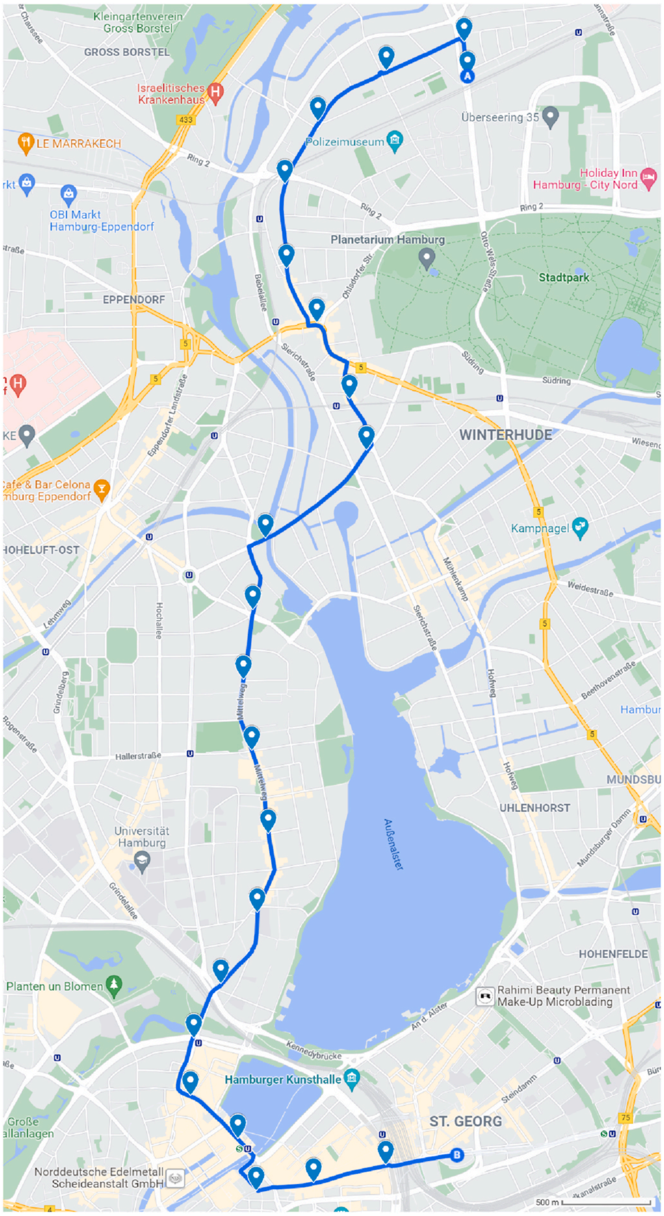

Fig. 10. Map of the route in Hamburg. (Maps Data: Google ©2022).

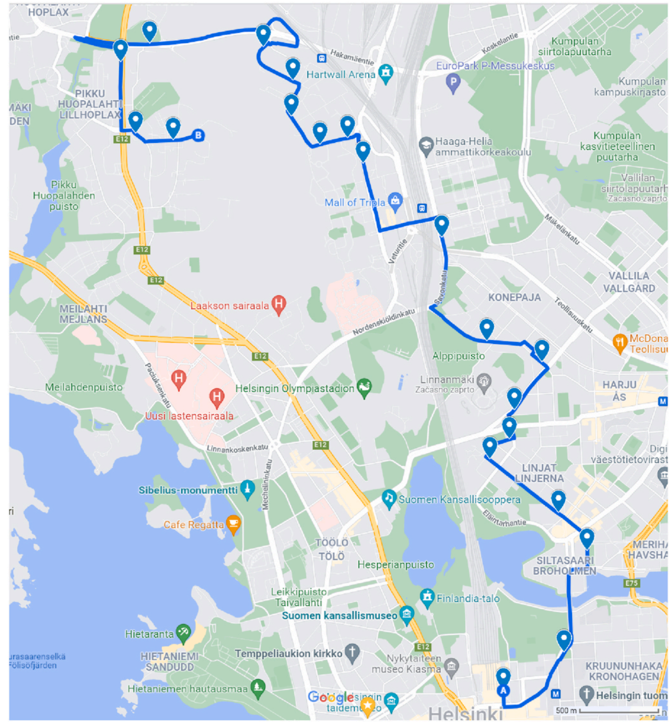

Fig. 11. Map of the route in Helsinki. (Maps Data: Google ©2022).

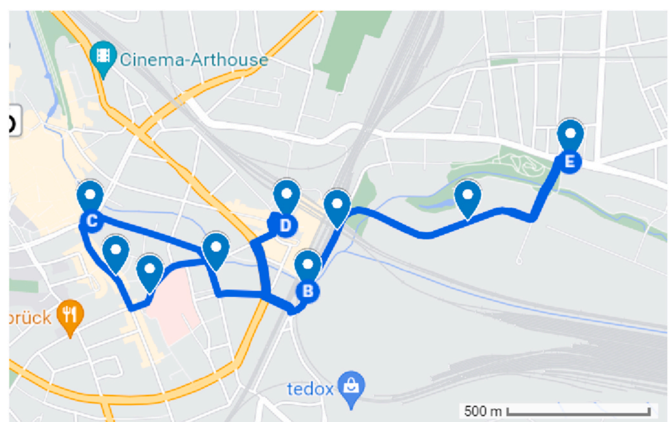

Fig. 12. Map of the route in Osnabrück. (Maps Data: Google ©2022).

At the end stations the buses are charged for 6–8 min using pantographs, before returning to the end station, where they are recharged again. A full charge gives the buses enough range for a return trip. Therefore, the buses can continue driving even if one of the charging stations is out of service, or if there is no time to charge the bus [33].

The climate of Östersund is cold and temperate. The temperature during the year varies by about around 23 °C. The minimum temperature is −12 °C and the maximum is 19 °C [111]. Temperatures below 10 °C are common for 10 months of the year.

4.2.10. Tartu, Estonia

In Tartu, test EBs operated on a short, 5-km, topographically flat route between the central bus station and the railway station (until August 2019) [112]. On this route (Line 25), there is only a short, slightly hilly section in the city center. The bus schedule was timed to match the timetable for the trains and the route was free of charge (14 trips each day).

A map of the route is presented in Fig. 14 and its elevation profile is shown in Fig. 15j.

EBs were tested on this route, with the charging achieved with a plug-in device. However, the bus had a roof-mounted pantograph to enable rapid charging [113,114].

Tartu's climate [111] is generally cold and temperate. The temperature averages 5 °C (min −10 °C and max 20 °C). Temperatures are below 10 °C for at least seven months of the year.

4.3. Challenges of the existing EB routes

The above review of EB routes in European cities indicates that there are too few benchmark routes under test that are really challenging from the aspect of seamless driving. Most of the above-described EB routes are not very demanding in terms of topography. Only two of them include shorter sections with ascents of more than 10% (i.e. the EB lines in Budapest and Hamburg). Even though some of the presented routes are located in regions with relatively harsh climatic conditions, they are generally not very demanding from the point of view of seamless EB driving. However, for test purposes, it should be better to look for such

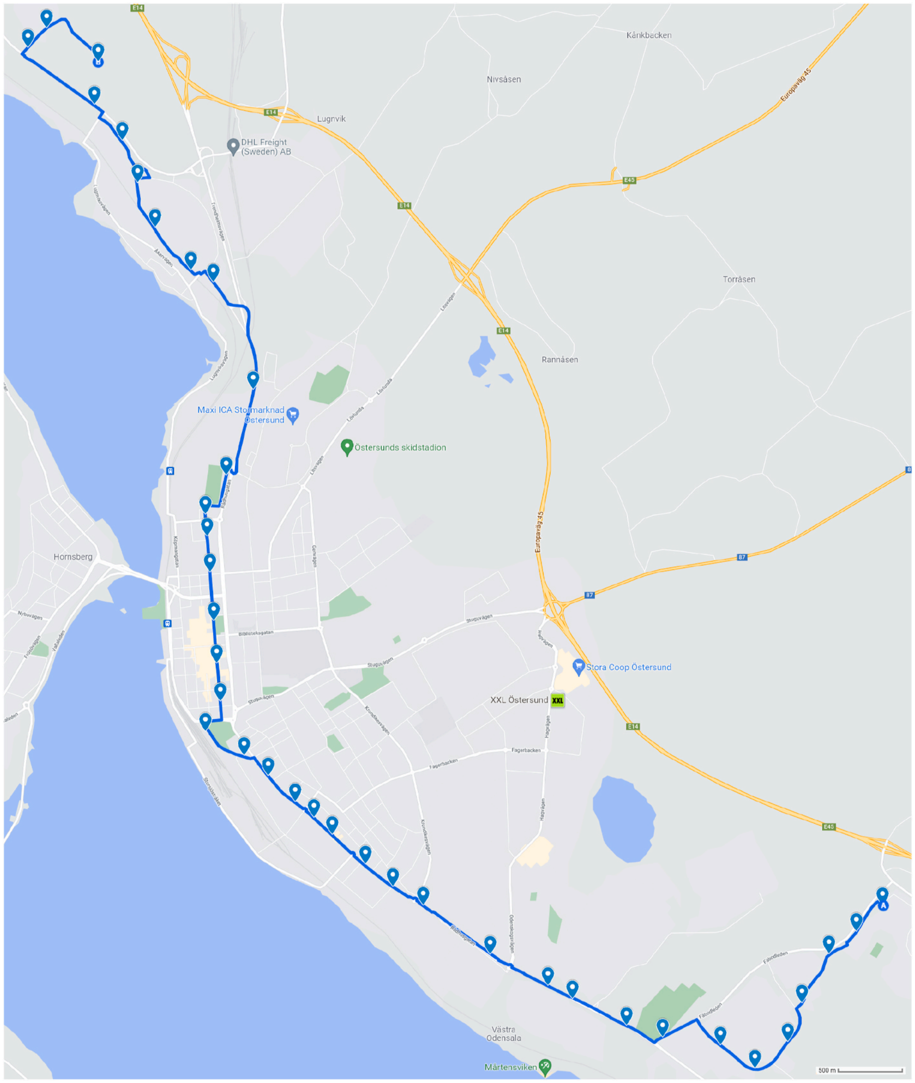

Fig. 13. Map of the route in Östersund. (Maps Data: Google ©2022).

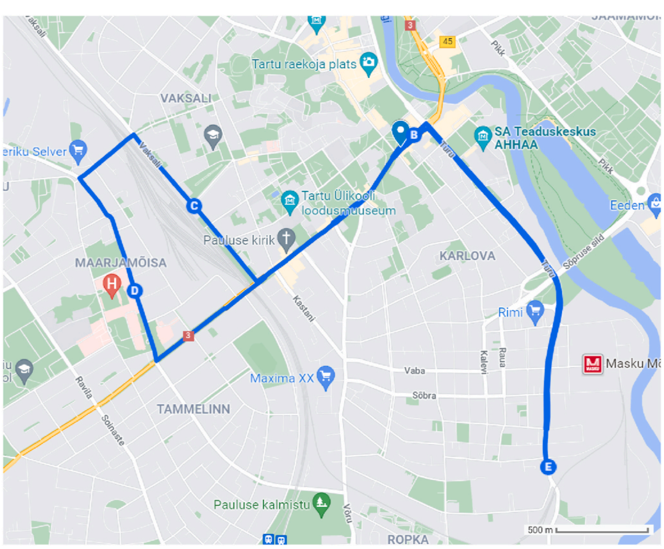

Fig. 14. Map of the route in Tartu. (Maps Data: Google ©2022).

routes that have both a demanding topography and harsh climatic conditions.

4.3.1. Elevation profiles

One of the characteristics emphasized for each exemplary city-bus route is its elevation profile. The elevation profiles of all the above-presented routes are in Fig. 15. The color legend in the elevation profiles follows the ranges presented in Fig. 15k: blue for descents of less than −12%, and red for ascents of more than 11%, in-between there are light blue (for descents of around −10%), green (for gradients between −7 and +3%), yellow (for ascents of around 5%), and orange (for ascents of around 8%). This same scale is used also for the elevation profiles in Fig. 17. It is easy to identify the elevation complexity of each route from the number of red-colored sections in the profile.

4.3.2. Climates

The ranges of daily temperatures recorded in the cities for the above-presented EB routes are given in Table 2. Temperature data were obtained from Refs. [111,115].

As indicated by the color legend in Table 2, the dark-blue color is for temperatures below zero (at which, according to Fig. 4, air-conditioning works at 100% of its power, as discussed in Section 3.4.2), the light-blue color is for moderately low temperatures (up to 10 °C), the white color is for moderate temperatures (between 10 and 20 °C) and red is for

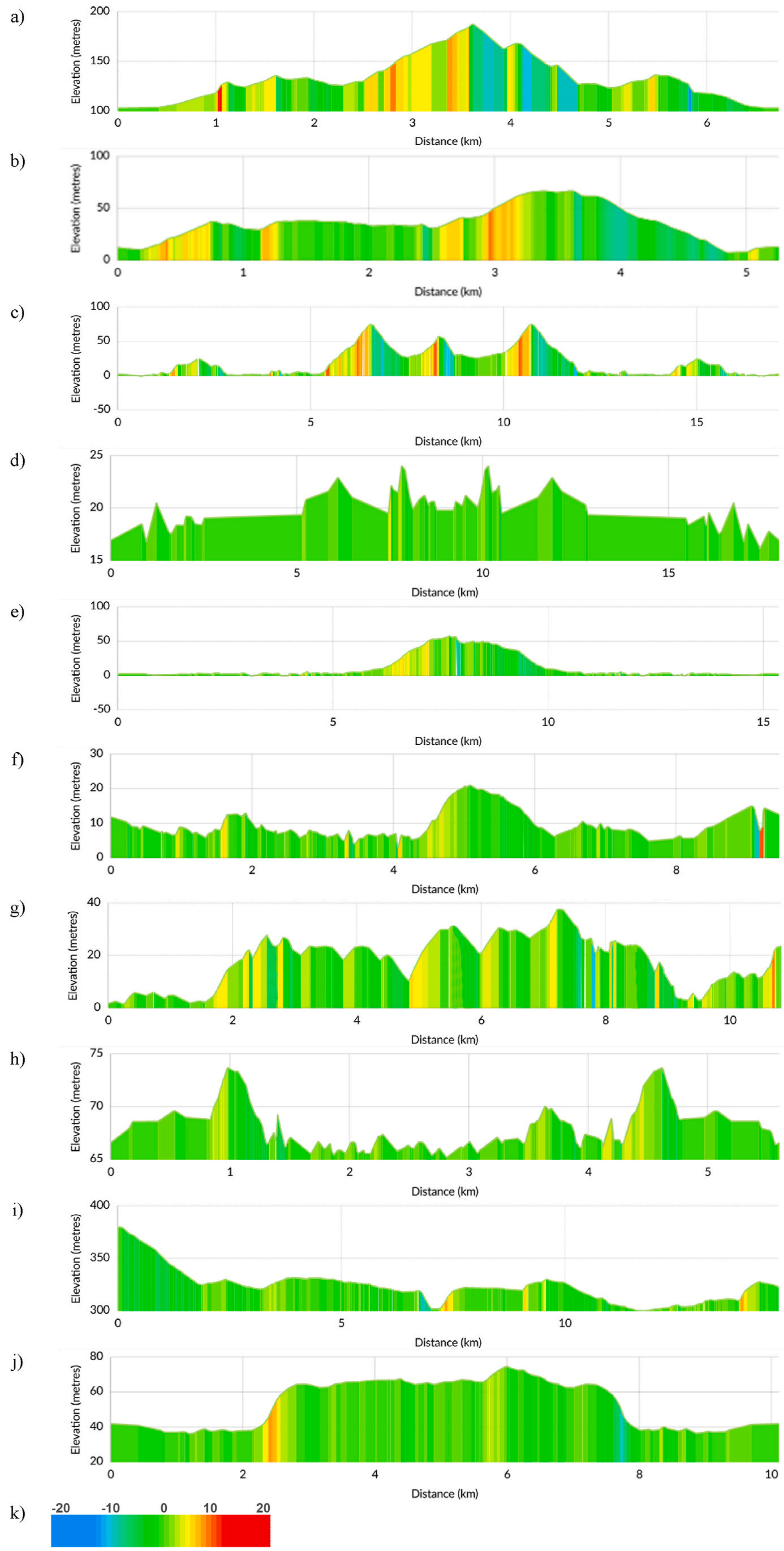

Fig. 15. Elevation profiles of the routes in a) Ävängen, b) Budapest, c) Cagliari, d) Eindhoven, e) Gothenburg, f) Hamburg, g) Helsinki, h) Osnabrück, i) Östersund, j) Tartu, k) gradient legend. (Note that the altitude y-axis is different for each route; a merged presentation is included in Fig. 18.)

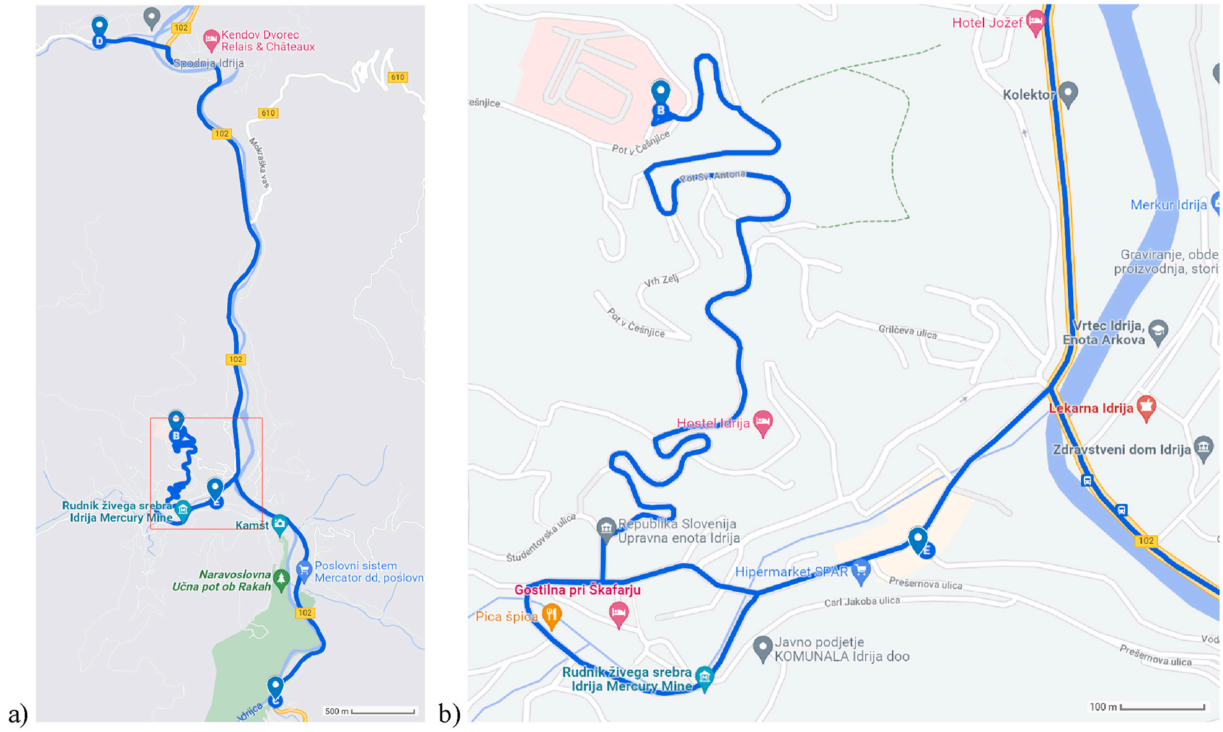

Fig. 16. Map of the Idrija bus route (Idrija – Hospital – Podroteja – Spodnja Idrija) and its characteristics: a) whole route, b) detail of the city center (marked in the left figure) with winding hill climb and descent. (Maps Data: Google ©2022).

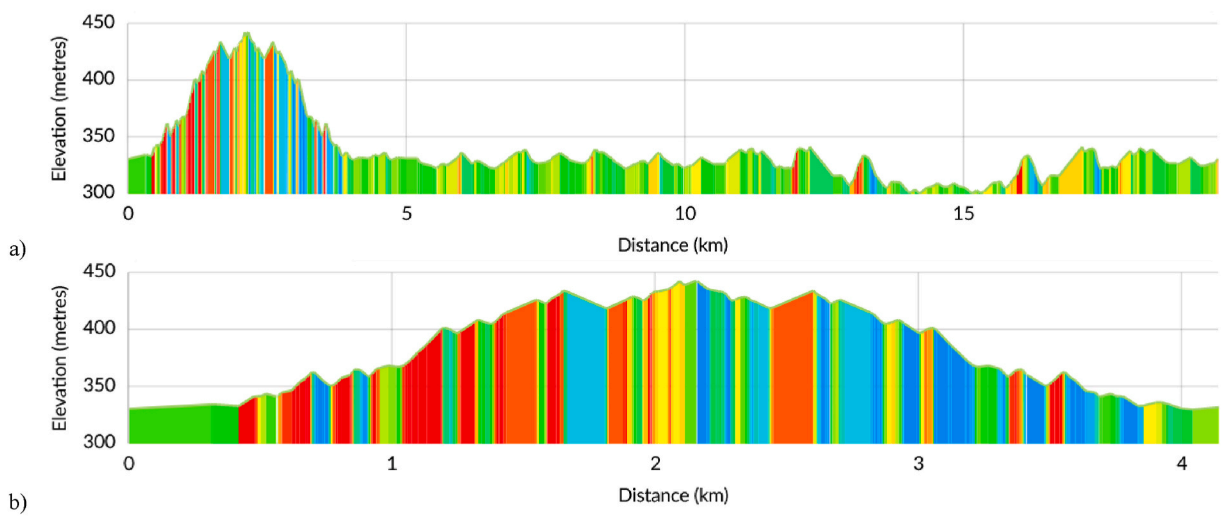

Fig. 17. Elevation of the route Idrija – Hospital – Podroteja – Spodnja Idrija and its characteristics: a) the whole route, b) the first 4 km (presenting the most critical and challenging sections of the route with the steepest climbs and the maximum ascending gradient of 25%). The color legend of the ascents/descents in % is presented at the bottom of the figure.

temperatures above 20 °C. Very low temperatures are critical because heating requires 100% power from the air conditioning and the performances of the battery under such conditions is seriously degraded [96]. In order to emphasize this situation, we colored the time periods in which the temperature falls below 0 °C with a darker-blue color. This color notation is also used in Fig. 20, showing a comparison of the climatic conditions for the selected city routes, i.e., the number of cold/hot months on an annual basis.

Proceeding from the characteristics of the EB routes presented above, we can conclude that among them there are no routes that would be very demanding and could be used by vehicle manufacturers and other testing infrastructures.

Therefore, we propose a new, demanding benchmark route in Idrija, Slovenia. There, the performance of a city's EBs and the associated charging infrastructure can be tested on a challenging route in a hilly area under the conditions of an urban driving regime.

4.3.3. Topography and climatic-conditions related energy consumption

The available reports and papers from which we extracted the data for this review do not give the same type of quantitative results or appropriate data that could be compared directly with each other. The quantitative data, such as consumption and other measured parameters, are obtained for different projects/approaches, different EBs and different infrastructures, used, built or adapted according to the specific

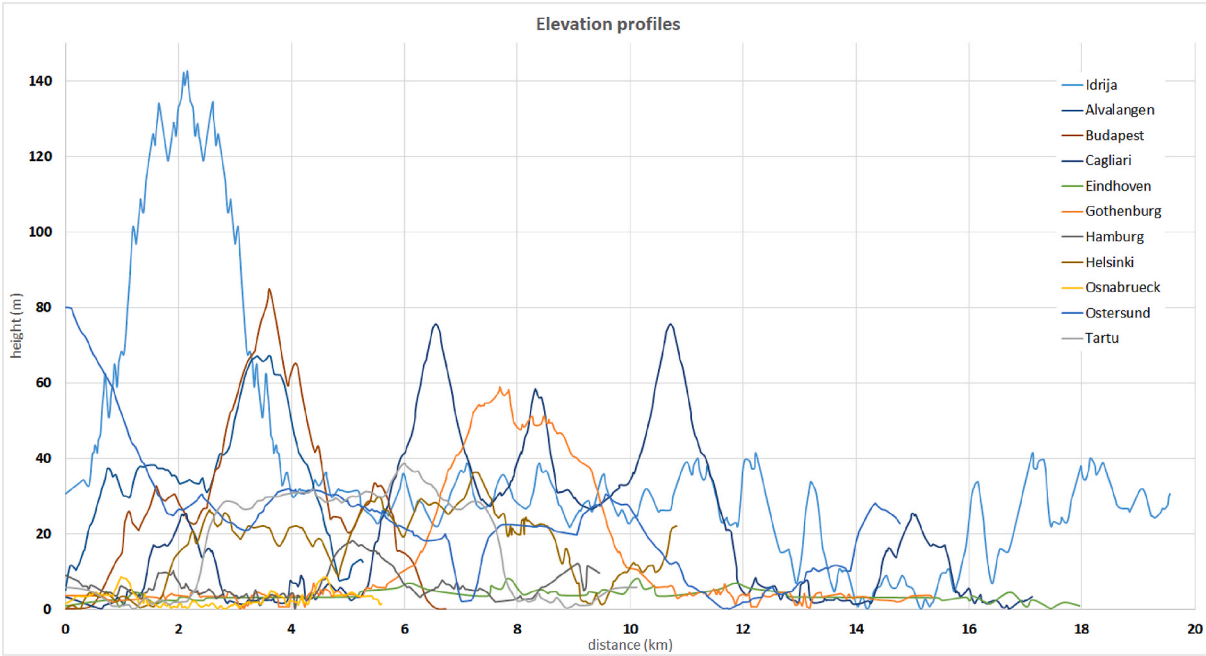

Fig. 18. Comparison of elevation profiles.

local needs, conditions and even local policies.

The presented comparison is based on an assumption that quantitative data on EB consumption on the above-discussed EB routes are similar to the data/trends presented in the open literature, i.e., to the results of several independent studies on the consumption of different EVs under different conditions (discussed in Chapter 3, Figs. 3 and 4). As evident from Fig. 3, the amount of the consumed energy on uphill roads is always significantly higher than the recuperated energy on downhill roads with the same slope and overall the analyzed experimental results indicate that the battery performance of EVs on hilly roads, despite the recuperation, is higher than on flat roads. As far as climatic/temperature conditions are concerned (Fig. 4.), it is also evident that lower temperatures greatly increase battery use, as well as under conditions when high temperatures require air conditioning to provide comfort for passengers.

In this paper we do not use any model to relate the slope and the ambient temperature to the battery use and to predict more accurately how these parameters influence the consumption, as was discussed in Ref. [116]. We believe that by using solely qualitative trends of the impact of climatic and topographical conditions on the EB's battery use someone can satisfactorily assess the demands of the presented bus roads. A more detailed analysis of the consumption along particular route segments is part of our future work.

5. A new, demanding benchmark route

The performance of a city's EBs and the associated charging infrastructure should be tested on a challenging route in a hilly area under conditions of an urban driving regime.

5.1. The Idrija city-bus route

The city of Idrija is considering the introduction of a new city-bus route to connect different parts of the town: the administrative part, the main hospital, the remote new part and the industrial park. The proposed route is based on combining existing routes, i.e., former routes and a current route that connects major parts. The EB route also takes in protected historical parts of the town.

The bus route starts at Idrija's main bus station (altitude of 330 *m*), goes through the historical center and stops in the main square, where the ascent of a winding road begins through one of the main housing areas of the city and arrives at the hospital at the top of the hill (450 *m*), where it turns back and descends to the historical center, drives around it and continues upstream along the Idrijca river past the main shopping center towards Podroteja (337 *m*). The bus then turns, drives downstream along the river, through Idrija's industrial park and on the main regional street to Spodnja Idrija (313 *m*), where it stops in the village center and in the industrial park. Finally, the bus turns and goes back to its starting point at the main bus station. The route is demanding because of the ascents and descents, the winding, narrow roads and the cold and snowy winters, which inhibit the normal functioning of the bus.

Benchmarking on the proposed Idrija conurbation bus route with its regime of urban driving in an undulating hilly area can provide valuable information as the EB, battery, charging infrastructure and management tools can be tested in the difficult situations of hill climbing, cold winters, winding roads, and acceleration. Since the route goes through the core zone of a UNESCO World Heritage Site, extremely low levels of noise pollution are required.

5.1.1. Route topography

The bus route in Idrija (Fig. 16) has the following characteristics: overall distance of 19.6 km, maximal altitude 443 *m*, minimal altitude 300 *m*, total ascent/descent 539 *m*, with maximal ascending gradient and maximal descending gradient of 25%. Its elevation profile is shown in Fig. 17. There are several steep ascending gradients in lengths of around 100 *m* each, where the steepest point is 25%. Note that the red color in the elevation profile of Fig. 17 indicates ascending gradients of more than 11%.

5.1.2. Climatic conditions

Idrija lies in a climatic zone with a long and cold winter period and relatively large variations in the outdoor temperature. According to ARSO [115], the maximum difference between the average highest daily and the average lowest daily temperatures is about 25 °C in a year. A typical change in average temperature over the year is given in Table 2, together with the data for the cites mentioned earlier. It is evident that the average monthly temperature is typically below zero in the winter months (December, January and February) and more than 20° higher in the summer months (June, July and August). However, the maximum difference between the winter and summer daytime temperatures can exceed 30 °C.

The daily temperature span can reach as much as 20 °C between the early morning hours and the early afternoon hours. For this reason, in order to achieve comfortable passenger travel, the battery is additionally burdened with air conditioning in spring and autumn, when the average temperatures are moderate. In this way, the Idrija benchmark route provides an opportunity to test EBs in challenging climatic conditions.

5.2. The Idrija route versus other electric-bus routes

In order to illustrate the main challenges and advantages of the route in Idrija, we compare it with the above-presented EB routes.

Firstly, we compare the routes in terms of their operational and topological characteristics. In terms of topography, the Idrija route is compared with the most demanding city routes in hilly regions. As is evident from the data listed in Table 1, it is clearly the most demanding within this selection. The elevation data in the table are based on Google Maps elevation services [99].

Although some of above-reviewed routes were classified as hilly, they are hardly comparable with the bus route to Idrija, which has a long, steep section with some extreme ascents of up to 25%. Some steep regions with an ascent greater than 10% can be found only in Budapest, Hamburg and Cagliari, but none of them exceeds 15%. Similarly, the difference in total altitude is far greater than in any of the presented exemplary routes. Fig. 18 presents the relative elevation differences for all the considered routes.

Fig. 19 presents the altitude difference, the sum of the ascents along the whole route, as well as the maximal gradient of the ascents. In combination with Table 1, we can see the largest difference in altitude, the highest cumulative ascents along the route, and the steepest gradients of the ascents on the Idrija route. These characteristics are much more extreme in Idrija than in any other city. From Fig. 17a it is also clear that there are many steep ascents in Idrija, especially in the historical part of the town.

To summarize, from Table 1, Figs. 18 and 19, it is evident that the categorization of a hilly topography is not clearly defined yet. However, comparing exemplary routes, where some of them are categorized as hilly, with the proposed Idrija benchmark route, we can conclude that Idrija serves as a good exemplary benchmark route with a very demanding topography.

Also, when we compare the climates in the above-mentioned cities, the conditions in Idrija can be ranked with the most challenging ones from the point of view of enabling the seamless driving of EVs (in terms of the battery use due to air conditioning).

The typical yearly temperature ranges in the cities with the EB routes compared above are presented in Table 2. The table shows the air-conditioning needs according to the environmental temperatures highlighted with red and blue color. It is evident that the Idrija climate requires the use of heating for most of the year and is comparable to the coldest of the above-mentioned cities.

5.3. Challenges and benefits of the benchmark route in Idrija

The hilly test route in Idrija has three advantages: (i) the proposed route has a more challenging topology and climatic conditions in comparison with the other hilly EB routes, which would be of great interest for battery and bus manufacturers that want to test their products on demanding real routes; (ii) the benefits to the region, i.e., the people of Idrija, without public traffic in the town center that has cultural sights – the test route would greatly reduce the number of passenger cars and the problem of parking in the historical town center; (iii) the EB route in Idrija also has a wider cultural significance as Idrija is on the UNESCO World Heritage List.

To implement the proposed benchmark route in Idrija, part of the current bus fleet can be replaced with electric versions of the buses currently operating on the route between Idrija and Spodnja Idrija, but the new route should also include some extended parts, as presented above, to cover the inhabited part of the historical center.

The intended charging infrastructure will include regular-speed chargers placed at the bus terminuses (and the depot) and also additional rapid-charging stations located on the steepest section of the route. To allow electricity to be taken from the grid at the most appropriate time, rapid-charging stations with powerful batteries will be built based on state-of-the-art pantographs that include powerful energy storage. Implementation of the necessary infrastructure along the proposed route in Idrija is feasible without significant space constraints or any other restrictions or expected problems.

5.4. Future work

The above review of EB routes in European cities indicates that there are too few benchmark routes that are very challenging from the point of view of seamless driving. The reason is that these routes were set by the development policies and projects that took place in different regions, and are therefore adapted to the possibilities, needs and current situation in each region. However, if we look from the point of view of the effective testing and comparative analysis of batteries, EBs, etc. Too, it would be helpful if we could find suitable polygons as reference routes where different manufacturers of buses as well as charging stations could perform their tests. As shown in Sections 4.3 and 5.3, the newly proposed road in Idrija could be an appropriate test polygon.

Since the presented comparison is based on data from the literature, in future work, we will supplement these data with further quantitative results on the specific technical parameters related to consumption in specific situations, which are out of the scope of this article. In a future project in which we intend to continue the activities related to the introduction of the EB route in Idrija, we would confirm the results of the analyses presented in this article with real measurements.

Table 1
Comparison of route characteristics in different cities. (The data for Hamburg, Helsinki and Östersund are for one direction only.)

	Distance (*km*)	Start/end altitude (*m*)	Max altitude (*m*)	Min altitude (*m*)	Total ascend (*m*)	Total descend (*m*)	Max ascend (%)	Max descend (%)
Idrija	19.6	331	443	300	539	539	25	25
Älvängen	5.3	12	67	7	85	85	9	8
Budapest	6.7	103	188	103	125	125	14	14
Cagliari	17.1	3	75	0	274	274	10	12
Eindhoven	18	17	24	16	44	44	4	4
Gothenburg	15.4	3	58	−1	137	137	7	10
Hamburg	9.5	12/13	21	3	86	85	11	11
Helsinki	10.8	2/24	38	2	172	151	9	10
Osnabrück	10.1	67	74	65	49	49	4	5
Östersund	14.8	380/323	380	300	92	149	8	9
Tartu	5.6	42	75	36	65	65	9	10

Fig. 19. Comparison of routes' topographical characteristics. Altitude difference is that between the minimum and maximum height on the route. Total ascent is the cumulative height of all the ascents. Max ascent gradient (on secondary Y axis) is the maximum gradient among all the ascents on the route.

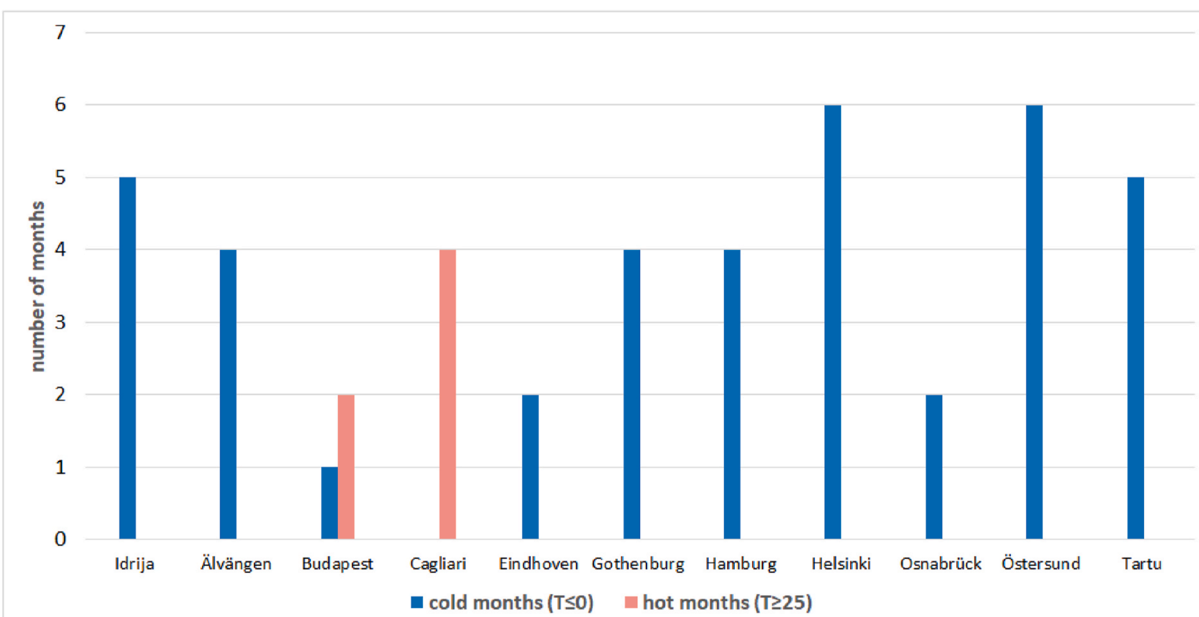

Fig. 20. Comparison of climatic conditions (the number of cold and hot months when air-conditioning is needed, according to Table 2.

6. Conclusion

The transition to electric urban transport is clear all over the world. There are several new technologies that are evolving and improving constantly. These technologies require a lot of testing to prove their reliability and their suitability for the particular usage. Electric buses (EBs) rely on high-capacity batteries that often require charging during the day and complex drive-train management systems that need to be tested under a wide range of road conditions and for different driving regimes set by road characteristics and climatic conditions.

The studies carried out by different authors suggest that the battery use of EVs is higher on hilly roads than on flat roads. Although simulations considering road parameters are very useful (especially in the infrastructure-planning phase), real-life tests on very demanding reference routes are still highly desirable for the equipment manufacturers and the planners of bus lines and infrastructure. In addition, recent research studies on the impact of climatic conditions on the energy consumption of EVs show that battery use is always higher in the wintertime when at the same time energy recovery is the lowest. From this point of view a consideration of the climatic parameters in the mathematical models improves the simulations; however, the physical testing of EBs in the regions with harsh climatic conditions give more

Table 2
Range of average daily temperatures in the considered European cities. The periods with the air-conditioning needs are highlighted. Temperature data source is [111,115].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Idrija	[-4.9, 0.6]	[-4.5, 1.7]	[-1.7, 5.1]	[1.7, 8.4]	[6.5, 14.1]	[9.4, 17.4]	[11.5, 20.0]	[11.6, 19.8]	[8.2, 15.5]	[4.1, 10.4]	[-0.7, 4.7]	[-3.6, 1.8]
Älvängen	[-3.7, 0.8]	[-4.3, 1.1]	[-1.8, 4.4]	[1.6, 9.4]	[6.6, 15.7]	[10.8, 19.4]	[12.5, 20.4]	[12, 19.9]	[9, 15.7]	[5.7, 11.2]	[1.2, 5.9]	[-2.3, 2.4]
Budapest	[-3.3, 1.6]	[-1.1, 4.7]	[2, 10.5]	[6.4, 16.8]	[10.8, 21.9]	[14.1, 24.8]	[15.6, 26.9]	[15.3, 26.4]	[11.8, 22.4]	[6.9, 16.2]	[2.5, 8.3]	[-1.1, 3.6]
Cagliari	[6.1, 13.5]	[6.1, 13.8]	[7.3, 15.6]	[9.2, 17.6]	[12.5, 21.8]	[16.2, 26.2]	[18.7, 29.1]	[19.3, 29.2]	[17.2, 26.1]	[13.8, 22]	[9.8, 17.6]	[7.3, 14.5]
Eindhoven	[-0.5, 4.6]	[-0.4, 5.4]	[1.6, 8.5]	[4.1, 12.7]	[7.9, 17.2]	[10.7, 20.3]	[12.3, 21.4]	[12.1, 21.4]	[10, 18.6]	[7, 14.1]	[3.1, 8.4]	[0.8, 5.2]
Gothenburg	[-3.5, 1.1]	[-3.9, 1.5]	[-1.5, 4.7]	[2, 9.6]	[7, 15.9]	[11.2, 19.6]	[12.9, 20.5]	[12.4, 20.1]	[9.5, 16.1]	[6.2, 11.6]	[1.8, 6.4]	[-1.6, 2.9]
Hamburg	[-2.6, 2.3]	[-2.6, 3.1]	[-0.3, 7.3]	[3, 12.6]	[6.6, 17.5]	[9.9, 20.7]	[12.2, 22.4]	[11.9, 22.1]	[9.1, 18.8]	[5.4, 12.9]	[2.3, 7.3]	[-0.6, 3.9]
Helsinki	[-8.2, -2.7]	[-8.6, -3]	[-5.4, 0.8]	[-0.1, 6.7]	[5.5, 14]	[10.6, 18.9]	[13.2, 20.8]	[12.3, 19.3]	[7.7, 13.8]	[3.5, 8.4]	[-1.2, 3]	[-5.6, -0.5]
Osnabrück	[-1.2, 3.3]	[-1, 4.1]	[1, 8]	[3.7, 12.6]	[7.7, 17.4]	[10.8, 20.6]	[12.5, 21.8]	[12.3, 21.9]	[9.9, 18.7]	[6.6, 13.9]	[2.7, 7.8]	[0.3, 4.7]
Östersund	[-12.8, -5.5]	[-11.6, -3.9]	[-7.7, 0.5]	[-2.7, 5.3]	[2.8, 12.6]	[7.9, 17.5]	[9.8, 18.7]	[8.8, 17]	[5.2, 11.6]	[1.2, 6.4]	[-4.9, -0.1]	[-9.6, -3.4]
Tartu	[-9.7, -4.3]	[-9.8, -3.6]	[-6, 0.8]	[0.3, 8.2]	[6, 15.9]	[10.5, 20.2]	[12.4, 21.5]	[11.6, 20.2]	[7.4, 14.8]	[3.2, 8.6]	[-1.6, 2.2]	[-6.5, -1.8]

legend	$T \le 0$	$0 < T \le 10$	$10 < T < 20$	$T \ge 20$

reliable results.

We looked at many benchmark EB routes in cities all over the Europe. While these city routes provide useful testing grounds, we believe that they do not provide EBs with sufficiently tough conditions in terms of distances, temperatures and road gradients. We propose a route in Idrija, Slovenia, which offers challenging ascents with gradients of even up to 25% placed in a region with a continental climate and long, cold winters and the high daily temperatures in the summer. Testing EBs and putting transport, energy-storage and charging systems into a single real-world benchmark would provide a comparable evaluation and validation of new technologies. The expected benefit of the benchmark results would be reflected in its influence on future developments (i.e., further improvements to technical solutions) and integration within similar geographically demanding areas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0098). The authors would also like to express gratitude to Municipality of Idrija and Matevž Straus for their contribution and support within the initial research and providing important information about the studied case.

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