ADVANCING PUBLIC TRANSPORT

KNOWLEDGE BRIEF

WIRES BECOMING CHARGING INFRASTRUCTURE FOR IN MOTION CHARGING

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INTRODUCTION

State-of-the-art in motion charging (IMC) trolleybuses are embracing a new technology for a new era of flexible yet high-capacity public transport. These electric buses charge dynamically while operating via an overhead contact network and can run on batteries for up to half of their route. Thanks to this, IMC trolleybuses have minimal battery size and weight, while their daily range is practically unlimited.

This Knowledge Brief aims to show cities how their existing trolleybus technology, with all its strengths and limitations, can be advanced with emerging IMC technology and a novel approach to holistic electric infrastructure development, while simultaneously ensuring the application of efficient, functional, trouble-free solutions proven in large-scale, real-life operational contexts. Furthermore, reaching zero-emissions goals can happen much faster in cities deploying IMC technology, since IMC buses scale very well.

This publication follows from the Knowledge Briefs "In Motion Charging Innovative Trolleybus", published in 2019, and the "Infrastructure for In Motion Charging trolleybus systems" from 2021.

THE IN MOTION CHARGING CONCEPT

For cities with an existing trolleybus network, IMC (an abbreviation belonging to Kiepe Elektrik), trolleybuses present many opportunities:

- Where diesel buses run under an overhead catenary system (OCS)* or make a connection to trolleybus routes, they can easily be replaced by IMC trolleybuses. This requires a relatively low additional investment in infrastructure.
- Existing overhead wires can be optimised by reducing the number of switches, turning loops, or non-regular service routes. Wires should remain where it energetically makes the most sense: busy routes, confluences of lines, and hilly sections. This approach increases the return on investment, reduces operating costs, and enables exploitation of advantages of IMC trolleybuses such as flexibility, unlimited range, dynamic drive, and lower vehicle weight.
- For cities that do not have OCS but are looking for a holistic approach to urban bus electrification, IMC buses can be valuable tools for specific applications such as pre-bus rapid transit (BRT) or BRT corridors, since their infrastructure is compatible with and complementary to opportunity charging and depot charging. Moreover, infrastructure for IMC trolleybuses can fulfil a wide range of other urban decarbonisation requirements such as electrifying shared mobility hubs or public street park charging.

* Heavy rail overhead wires are technically referred to as catenary, including with supporting wires and longer distances between supporting masts. Trolleybuses, similar to light rail, use a simplified contact wire. Since this is internationally referred to as OCS, the decision has been taken to use this terminology here.

Several hundred cities around the world operate conventional trolleybuses. Their power networks consist of substations, cables, and overhead wires. In many cases, major parts of the electric feeding infrastructure can be shared with rail transport, especially light rail, often under the same public ownership. This makes this infrastructure a public asset of extraordinary strategic importance. IMC technology presents new opportunities for the increased use and value of this infrastructure.

The IMC concept is well-adapted to existing trolleybus systems, having been adopted for quick route extension and rapid decarbonisation by cities as diverse as San Francisco, United States of America; Vancouver, Canada; Salzburg, Austria; Zurich, Switzerland; Bergen, Norway; Landskrona, Sweden; Lyon, France; Shanghai, China; Prague, Czech Republic; Solingen, Germany; Budapest, Hungary; and Genoa, Italy. Most existing OCS cover central areas, with battery operation on less frequent routes on the outskirts.

ELECTRIFYING BUS NETWORKS: STRENGTHS OF IN MOTION CHARGING WITHIN A MIX OF BUS ELECTRIFICATION TECHNOLOGIES

IMC technology is also suitable for rapid electrification of diesel bus systems. Insights and experiences from large-scale electrification projects indicate that the "one size fits all" approach from the diesel bus era no longer works in many cases if decarbonisation is targeted not just as a "quick fix", but rather as a sustainable, long-lasting economic and environmental success. Thus, a careful network analysis covering all possible combinations of available electrification technologies is the foundation for a truly holistic approach to bus decarbonisation. Opportunity charging, depot charging, and IMC should be combined to exploit their potential synergies, both in terms of infrastructure deployment and urban planning. Within one network, IMC is particularly suitable for medium- to high-demand corridors where several routes overlap, BRT-like operations, and hilly terrain.

When combining electrification strategies in a holistic demand and supply forecast analysis, strengthening urban corridors is of critical importance for transport-oriented urban design (TOD). A bus corridor will ideally foster demand by attracting both residential and commercial real estate and activities, reinforcing its use and triggering a virtuous circle. If such corridors are equipped with OCS, buses can be charged while using them, thus eliminating waiting time for static chargers in high demand. The key idea here is that most or all buses serving such a corridor can use the overhead wires for recharging, even if such wires are only available on a fraction of their route.

BEYOND THE TROLLEYBUS - KEY ASSETS OF IMC BUSES

- Alignment of economic and environmental advantages: A typical 12m/40ft IMC bus requires a battery of about 60 kilowatt-hours (kWh); a depot charger, on the other hand, needs a 600-700 kWh battery. Thus, charging via an OCS through IMC reduces the required bus battery size, and, consequently, the amount of primary composites needed, by a factor of ten compared to depot charging buses. Lighter vehicles, in turn, lead to better performance and less wear and tear and reduce operational, environmental, and geopolitical costs and risks.
- Infra-Lite: New systems can largely be built without overhead wire switches or crossings, making OCS infrastructure much cheaper in terms of investment and ongoing maintenance than legacy trolleybus systems – real-world experience indicates that sets of overhead wires can last four decades or longer without major renovations. Legacy systems can progressively be adapted to remove some switches or crossings, making them visually less intrusive and reducing maintenance costs. Freed up funds can be used for new wire sections where they are most beneficial, e.g., along newly electrified corridors.

A state-of-the-art, 24 metre long double-articulated IMC bus in Linz, Austria is an efficient solution to capacity with a small battery of only 60kWh.

IMC charging is synergetic with other charging modes; some opportunity charging buses can recharge on overhead wires (2-pole charging), and IMC buses can use certain opportunity charging substations to extend their off-wire capabilities. Furthermore, IMC feeder infrastructure can be used by other charging facilities adjacent to the route such as street parking, which significantly reduces the costs for both in holistic urban electrification plans.

IN MOTION CHARGING AS THE BACKBONE OF A WIDER URBAN MOBILITY ELECTRIFICATION STRATEGY - RE-USE AND MULTIPURPOSE USE OF INFRASTRUCTURE

IMC buses' peak energy demand is lower than that of other types of electric buses, and they have the highest utilisation rate of charging infrastructure.

- Vehicle procurement and markets: IMC buses do not require vendor-specific charging protocols linking them to a specific manufacturer. They have all required charging intelligence on board and can work with any OCS infrastructure, giving owners and operators broad control over tendering processes.
- Compatibility with other electric charging modes: IMC trolleybuses can co-use specific opportunity chargers for a quick recharge when far away from overhead wires, and opportunity charging buses can recharge from an OCS. Specific remote chargers for IMC bus use can be built for as little as €50k.
- Flexible operations: IMC buses can overtake others in revenue service, allowing for a reduction in the number of parallel wires in each direction. While de- and re-wiring during passenger boarding only takes seconds, current industrial research in Germany is focused on enabling re-wiring while IMC buses are running.
- Visually non-intrusive: OCS can be deployed in a way that is visually non-intrusive. Innovative best practices and citizen feedback have led to solutions such as an OCS being hidden under tree canopies to combat urban heating or used as a deliberate urban design element to draw attention to the presence of a high-capacity bus corridor. Other successful approaches include integrating OCS with public lighting, making it a streetscape-enhancing asset fostering a local visual identity. Such strategies are widely used in light rail deployment and have been well-received on both technical and political levels. They require careful urban design interventions developed in cooperation with architects and urban designers.
- Planning, training, and operational synergies with rail: Where other electric public transport systems such as metro or light rail are operating, core knowledge for planning and running an IMC charging system is locally available with planners and staff. Furthermore, key infrastructure such as existing 600 or 750 volt (V) direct current (DC) substations, used in many tram and metro systems, can often be co-used for IMC.
- Excellent scalability: Once an OCS is in place, IMC is a charging technology that scales well while maintaining its operational robustness and flexibility, making it particularly attractive for large fleets and intense service requirements.
- Easier planning and more stable power grids: Planning, e.g. regarding the installation of feeder substations, is more flexible and less demanding in terms of capacity. The stability of the electric grid, which is of growing concern due to the increasing charging demand from electric vehicles (EVs), can be influenced in real-time through connected IMC buses' batteries (for a state-of-the-art overview, see the SwissTrolleyPlus project).

While the initial investment required for OCS infrastructure can be higher than for pure battery electric bus infrastructure, a trolley grid for IMC can be shared with other public transport modes such as light rail. Moreover, due to IMC buses only requiring an OCS on 30-40% of their service route, an OCS for IMC can serve a much wider functional urban area than traditional trolleybuses do, making it a quick-to-implement and efficient tool to transition to zero-emission vehicles.

Cities with existing overhead wire infrastructure for metro or light rail can, in many cases, use existing feeder substations for IMC, reducing the need to enhance the grid capacity. IMC deployment also decreases the peak demand for overnight charging, since IMC charging is significantly more efficient in a grid-to-wheel comparison, further contributing to grid stability.

The sharing of existing charging infrastructure can be realised through alternative business cases like in Arnhem, Netherlands, where DC-DC charging through overhead wires for trolleybuses is used to power fast chargers for other EVs, showcasing the broad use cases of IMC infrastructure beyond buses alone.

Furthermore, DC-alternating current (AC) coupling for supplementary electric devices such as TVMs, WiFi access points, or variable-message sign (VMS) travel information boards are powered using trolleybus contact lines. This logic can be expanded to other urban electrification requirements. It saves costs for local power suppliers through limited infrastructure upgrade requirements, reduces the need for expensive below-ground works for connections to the local power grid, brings new connections, and contributes to better use of existing capacity. Moreover, an IMC OCS not only helps combat the current energy and climate crisis but also brings significant economic and environmental benefits for broader city decarbonisation strategies.

DC fast charging hubs are especially important in cities to enable EV adoption, which was explored in the Horizon 2020 project ASSURED*. Since the system is DC-DC, it has less energy loss than traditional charging systems. Thus, EVs can be charged in a highly sustainable way. In this regard, IMC infrastructure should be viewed as part of the energy network as much as it is part of mobility solutions serving an entire functional urban area.

An 18m IMC trolleybus operating in eBRT service in Beijing, China. Beijing has 2 out of 3 BRT routes electrified with IMC technology.

NEW IMC DEPLOYMENT: THE PRAGUE CASE

Designing and building light overhead wire sections: deployment, integration with other bus electrification technologies, and blending into an urban landscape.

Since 2011, the Prague Public Transit Company (DPP) has been testing alternative drivetrain and vehicle types to find a solution that is operationally functional, technically reliable, and economical under the local conditions.

Based on this analysis, along with the experience of colleagues in other cities, DPP concluded that the most effective tool for reducing energy consumption in transport would be the replacement of internal combustion engine (ICE) (guideline efficiency value of 30%) buses with electric traction buses (75% efficiency), which would facilitate the provision of locally emission-free transport, overall reduction of carbon dioxide (CO2) emissions, reduction of noise pollution, internal synergies with the tram power system, thus improving the efficiency of investment and operating costs, and increased overall energy security in Prague due to reduced dependence on fossil fuels.

Within this scope, DPP found the most technically and operationally advanced and operationally robust technology to be IMC using battery trolleybuses, complemented by opportunity charging using two-pole charging technology.

Prague's specific context includes the following:

- **Rugged terrain:** Buses have to go up and down steep gradients along their route, the vertical height difference between the Vltava River and the highest points being over 230m on each trip.
- **Long routes and high daily mileage:** length of routes often exceeding 20km, with daily vehicle mileage exceeding 300km/day.
- **High demand and dense service intervals:** Bus routes mostly have very short intervals, are operated with articulated vehicles, and do not offer sufficient time at the terminals to allow for static charging.
- **Long daily service hours:** The bus service runs from 4:30 to 12:30 a.m., with the last buses pulling into the garage around 1:30 a.m., so even full overnight charging is not possible.
- **Large fleet:** The large fleet of 1,200 buses requires a charging technology that scales well, which IMC does.
- **Electric air conditioning (a/c) and heating:** Heating in the winter increases electric energy consumption by up to 100%. The City of Prague requires fully emission-free vehicles, which an electric bus heated by a diesel unit is not.

* Public deliverables on multipurpose use of public transport infrastructure from ASSURED and EfficienCE

Based on the abovementioned context and analysis, DPP has opted for bus electrification primarily through battery trolleybuses (IMC), complemented by two-pole charging battery buses (opportunity charging). With the rising pressure on the economics of bus operations, e.g. due to autonomous vehicle (AV) robotaxi deployment, efficient and scalable solutions for electric bus operations are required, making the Prague case a reference for future investment decisions of comparable scope in other cities.

COMPLETED AND UPCOMING PROJECTS

The abandonment of trolleybus transport in Prague in 1972 resulted from a political decision, not from an assessment based on technical analysis. Today, thanks to a comprehensive technical reassessment of electrification challenges, DPP is preparing IMC-based bus route electrification projects in various parts of Prague, starting with the airport routes 119 and 140. The deployment is aligned with other infrastructure projects and includes the coordinated modernisation of public lighting, combining lighting, and OCS masts to save funds and minimise impact on public space.

The new IMC buses will use the OCS for both propulsion and charging. OCS wires are only being implemented where absolutely required (see graphic); on half of the route, IMC buses will be able to draw energy from their traction batteries, instead.

The project has also made use of a formerly defunct asset; a substation from the former trolleybus network has returned to its original use after more than 57 years. In combating the climate crisis, asset management is becoming a key element of sustainability management.

The longevity of IMC infrastructure components is, as for rail, an economic and environmental advantage.

An IMC bus passes through the historic city centre of Bergen, Norway, on battery. Outside of the city centre, the OCS charges the battery and helps the bus up steep gradients.

ENERGY MANAGEMENT RESOURCES, INTEGRATION OF RENEWABLE ENERGY SOURCES, AND SMART GRID TECHNOLOGIES

Electricity demand in urban areas is projected to grow substantially due to increased use of EVs in all forms. Similar to the abovementioned SwissTrolleyPlus project, the operator PKT Gdynia in Poland has been actively working on using smart grid technologies in their trolleybus traction network, which also fits into the ELIPTIC project framework.

In this ecosystem, IMC trolleybuses enable two-way energy flow by not only receiving but also supplying energy* back to the grid. The power system of public transport can thus play an active role in creating power islands, which constitute an element of modern intelligent power systems. Like solar power from photovoltaic (PV) systems, energy recovered during braking, which may also be regarded as renewable energy, is another source of energy for vehicle charging*.

The synergy of these energy management, renewable energy generation, and smart grid solutions enables the expansion of energy efficient operations with relatively low investment, and the trolley grids are well-equipped to play the role of an overall grid in the city. A smart trolley grid thus allows for bilateral energy supply, optimised usage of recuperation energy by balancing energy flows, the leveling of voltage drops, and testing of energy storage concepts integrated into trolley grid substations (see Gdynia, Pilsen - Interreg project EfficienCE). The emissions associated with supplying energy to the existing trolley grid equal about 2000 tonnes (t) of CO2 per year. The analysis conducted within the project identified the possibility of installing charging stations for third-party devices across practically the entire trolleybus network.

In summary, smart trolley grids are part of a wider urban distribution network. We therefore need to consider future grids as stakeholders in an overall urban energy system, taking into account where PV, EV chargers, and storage will be installed and how these components will interact with a trolley, tram, and rail OCS. Considering the calculation and monitoring of lifecycle emissions, energy management plays a significant role in the overall greenhouse gas (GHG) emission cycle.

OCS DEPLOYMENT - THE STOCKHOLM STUDY

The results from the Stockholm study indicate that IMC is efficient on routes longer than 7km and with a headway of ten minutes or less. To optimise each route, the following is required:

- At least one of the **terminuses should be equipped with overhead wires** or a static charger (for IMC, these can be built for approximately €50k).
- Each route should have **around 40% of the length covered by OCS** charging infrastructure, with exact numbers depending on the way routes overlap. To decide where OCS sections should be deployed, the battery size (as small as possible) and time needed to charge the batteries are crucial factors that need to be balanced.

The **most used parts of the system** are often located in city centres. If an OCS is not deployed in a city centre, it will need to serve outside sections and will increase in overall length, but simultaneously will be easier to build and implement.

FULL OR PARTIAL INFRASTRUCTURE – DECISION-MAKING PARAMETERS AND PROCESSES

A 2019 study in Stockholm, Sweden compared different charging approaches and found that depot charging required 10-25% more vehicles than basic diesel bus operations. IMC requires the same number of vehicles as diesel operations, but operators need to build charging infrastructure in parts of the network. The more buses run in the same streets, the more efficient the use of the infrastructure will be (the so-called corridor approach). Stockholm has six trunk routes with a headway of 4-5 minutes. Thus, for a total route length of 41km, 15km of OCS charging infrastructure would be required, mainly on roads operated with at least two trunk routes.

The following are three examples of different strategies to electrify a city bus network, all based on existing trolleybus infrastructure:

* Wolfgang Backhaus, Henning Günter, trolley:motion, Final Project Brochure: Results, Trolley 2.0 Public Deliverable, AND Mikołaj Bartłomiejczyk, Bilateral power supply of the traction network as a first stage of Smart Grid technology implementation in electric traction, 2018

In Rimini, Italy, a new eBRT (electric BRT) routeof 9.8km opened in 2021, running almost exclusively on dedicated right-of-way. Route extensions are currently being planned.

- In **Bergen, Norway,** the key bus route, opened in 1950 as a trolleybus route, was extended by 6km in 2021 into the hilly terrain surrounding the city on both sides. The extension passes through the city centre on 2km of length without overhead wires. Ten new IMC buses are running on the route.
- In 2020, trolleybuses in **Esslingen, Germany** had 14.4km of overhead wire and two routes. To electrify all urban bus operations, a total of 5km of new wiring is currently being installed, and 46 new IMC trolleybuses of 12m and 18m length are on order. They will be supplemented by opportunity charging buses operating on more remote and infrequent routes, with synergies in charging infrastructure.
- **Solingen, Germany**, which has an extensive trolleybus network for a city of its size, is electrifying all urban bus routes exclusively through the procurement of IMC buses.

Other decision-making parameters in a holistic bus electrification approach include local factors such as network topography. A hilly terrain or routes climbing considerable heights are ideal cases for in motion charging, since the net vehicle weight (without cargo/passengers, but including fuel/batteries) disproportionately affects energy consumption. In this case, the deployment of OCS on the steepest parts of the routes should be considered – doing so greatly reduces operational costs compared to other modes of electrification while simultaneously providing much higher capacities.

Furthermore, geopolitical aspects should be taken into consideration. For example, sourcing raw materials for batteries can be challenging, particularly from a political perspective, making it another incentive for minimising battery size and usage. Moreover, current global projected demand for batteries in transport alone exceeds the planetary availability of lithium resources, with such calculations already factoring in realistic projections of future improvements in battery technology.

COMPARATIVE COST ANALYSIS

THE POST-DIESEL AGE: SYNERGISTIC COMBINATION OF CHARGING TECHNOLOGIES

As previously mentioned, an economically and ecologically viable, robust, and holistic approach to bus electrification will, in most cases, entail a combination of several charging technologies, resulting from a detailed analysis assigning different types of charging modes to different route typologies.

Typically, for low-frequency, low-demand routes, **mid-size depot charging vehicles** are the overall best choice, whereas for medium-frequency routes not serving central corridors, **opportunity charging buses** are usually the best fit. For medium- to high-frequency routes up to and including BRT services or routes serving major corridors for 30% or more of their travel time, **IMC buses** are often the best choice - this is where a carefully planned, strategic deployment of OCS infrastructure segments makes the most sense from an urban design, as well as operational and economic, point of view.

Hydrogen fuel cell buses, which according to their operational profile are closest to diesel buses, may also be a valuable tactical complement in some cases.

Overall, a technical, analytical approach to selecting different options for bus electrification will make the planning robust when exposed to political considerations.

IMC COST STRUCTURE: KEY ELEMENTS

The cost of specific systems and applications is highly dependent on local conditions, such as topography, service standards, local labour costs, raw material and processed product markets, climate, right of way conditions, local availability of public lighting supporting the OCS, and other local governance aspects. Some key capital expenditure (CAPEX) and operational expenditure (OPEX) data points and ranges taken from industry and academia are summarised in Tables 1 and 2 below in an anonymised form:

Table 1: CAPEX examples for core IMC cost values, in EUR (2023)

COMPONENT	COST (LOWER END)	COST (UPPER END)
* OCS setup per linear km (0.62 mile)	100,000	1,000,000
12m (40ft) standard IMC bus, purchase	300,000	650,000
18.75m (60ft) standard IMC bus, purchase	550,000	1.000,000
24.5m (80ft) standard IMC bus, purchase	700,000	1.200,000
IMC feeder substation, setup	(MVA 1) 850,000	(MVA 4) 1,500,000
IMC charger, away from OCS, setup	50,000	mainly depending on cost of ground

Table 2: OPEX examples for IMC core cost values, in EUR (2023)

COMPONENT	COST (LOWER END)	COST (UPPER END)
* OCS maintenance per linear km (0.62 mile) per year	2000	6000
IMC feeder substation, yearly maintenance	2000	5000

* 2x2 wires suspended, excluding switches and crossing

OCS COSTS

80% of OCS costs are typically for supporting masts. Thus, the local availability e.g., of public lighting that is structurally able to carry an OCS and/or a local law forcing building owners to allow for fixing OCS on their facades where suitable has a major impact on setup costs. Similarly, many switches, crossings, and turning loops can be made redundant through proper planning of OCS sections and feeders, greatly reducing both setup and maintenance costs.

Furthermore, the fact that even for a BRT-level operation, OCS segments are only required on approx. 25-50% of the route improves the economics of IMC compared to traditional trolleybuses.

End of an OCS section on charging road in Beijing, China: Buses dewire while running. Note OCS visually absorbed by urban tree canopies.

Station on an eBRT corridor operating with IMC trolleybuses in Beijing, China.

KEY SYNERGIES WITH OTHER BUS ELECTRIFICATION TECHNOLOGIES

With IMC, it is possible to plan for scheduled bus services to operate far away from segments under overhead feeder wires, with **state-of-the-art vehicles typically able to run up to 25km** on batteries, under maximum passenger load and with heating/a/c fully running.

If such off-wire routes are particularly long or in the case of flexible service routes, e.g., for late evening services, IMC buses can use chargers for a few minutes to recharge their batteries, e.g., at a terminal.

For such chargers, two options exist:

- Using a **combined opportunity/IMC charger** that can boost both trolleybuses and opportunity charging buses. Such chargers typically require the full set of electronics for pantograph charging of opportunity charging buses and are comparably costly.
- Using a **specific IMC charger** built from standardised industrial electrical equipment components, allowing for easy local tendering. Given that the charging electronics of IMC trolleybuses are onboard, the cost for such chargers of a comparably simple and robust design is much lower than for combined chargers.

  The City of Cagliari in Italy quotes a cost of approximately €50,000 for a charger that enables extension of a trolleybus route to a low-density beach area where OCS setup would not have been possible.

  Similarly, some **opportunity charging buses can use a trolleybus OCS segment to recharge**, provided they have the appropriate electronics on board. This has been implemented in various locations, including Vienna, Prague, and Cagliari, among others.
- In areas such as **workforce training and knowledge management, depot adaptations, maintenance, and safety procedures,** other important synergies exist.

VEHICLE LONGEVITY

In Neuchâtel, Switzerland, the first generation of partly low-floor single articulated trolleybuses has exceeded thirty years in revenue service. Secondhand vehicles can reach lifetimes exceeding 50 years, which is a significant argument not only in terms of economics, but also environmental sustainability.

For IMC trolleybuses, one or two battery upgrades need to be factored in for a 15-20-year service life. Since IMC batteries are comparably lightweight, (e.g. 1.1t/2,450lbs both for a 18.75m/60ft and 24.5m/80ft IMC bus, compared to 4.6t/10,100lbs for an 18.75m/60ft depot charger in Zurich, Switzerland), their integration into buses should not dynamically alter or affect the static structure of the vehicle body, which can be a significant problem with battery-only buses.

Off-wire section of major charging road corridor in Beijing, China: An OCS section commences mid-picture. All buses in the picture are IMC trolleybuses.

Table 3: Key advantages of IMC operations

COMPONENT	ADVANTAGE
Vehicles	*Lower weight due to smaller batteries
	Double articulation possible at high frequency and on rough terrain
	**Lowest number of vehicles needed for similar operations
	***Charging intelligence onboard – competitive option in supply market and prevention of vendor lock-in
Charging infrastructure	****OCS deployment required only on approximately 30-40% of linear route length
	OCS for IMC, largely without switches and crossings, is cheaper to build and visually non-intrusive
	OCS setup cost typically reduced by up to 90% if installed on building facades or existing public lighting that is statically fit > cost-effective and speedy deployment
	Good scaling of service with no further infrastructure investment once OCS segments have been established - additional vehicles can be added at no significant extra cost
	Lifetime of 40+ years without major overhaul
	No time slot management for stationary chargers necessary, as would be the case for high-capacity opportunity charging
	Synergies between opportunity charging and IMC on same chargers possible
	Specific IMC "far from OCS" chargers are up to 20x cheaper to set up than opportunity chargers due to reduced complexity in electronic charging control systems
Service externalities	Feeder cables for substations can be used for other functions along route, facilitating the implementation of broad urban electrification strategies at significantly lower cost by combining public works processes
	Corridors with IMC make high-frequency service intuitively visible, producing a virtuous circle in residential and commercial real estate deployment that raises demand levels, resulting in wider public benefits for every infrastructure dollar invested
	Leveraging of local real estate since OCS is perceived as a long-term service commitment

Main urban corridor in Beijing, China, illustrating the 'charging road' concept: Overlaying IMC trolleybus routes operate at high frequency in mixed traffic on a single set of wires, allowing for charging and overtaking with off-wire operation.

* This advantage will remain with progress in battery technology, even if the overall gap will decrease; research from solid state physics shows that while incremental improvements on the size/weight vs. performance ratio of batteries will continue, changes by multiple of integer dimensions are not to be expected for batteries complying with heavy road transportation requirements.
** Referring to electric charging technologies. Assumption: medium- to high-frequency service
*** Comparison with other electric charging technologies
**** Varies based on local conditions, thus subject to detailed analysis

CONCLUSIONS AND RECOMMENDATIONS

As summarised in Table 3, IMC operations present many advantages to cities to advance their trolleybus operations. Major parts of the electric feeding infrastructure can be shared with rail transport and new urban power applications, often under the same public ownership. This makes this infrastructure a public asset of extraordinary strategic importance.

IMC can serve as the backbone of a wider urban mobility electrification strategy and is also suitable for rapid electrification of current diesel bus systems. A careful network analysis covering all possible combinations of available electrification technologies is the foundation for a truly holistic approach to bus decarbonisation and makes new IMC trolleybus routes a key tool: Opportunity charging, depot charging, and IMC should be combined to exploit their potential synergies, both in terms of infrastructure deployment and urban planning.

IMC's synergetic integration with other electric charging modes, alongside the opportunity for highly flexible operations, its options for visually non-intrusive deployment, excellent scalability means that this technology can facilitate the transition into in a new era of flexible and high-capacity public transport.

New bike and trolleybus corridor as a campus 'living street' in Seattle, United States of America.

This Knowledge Brief was prepared by the Trolleybus Committee members Per Gunnar Andersson, Wolfgang Backhaus, Arnd Bätzner, and Jiří Kohout, with the collaboration of Jan Barchánek and Richard Kayser.

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This Knowledge Brief was prepared by the Trolleybus Committee.

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