trolley:2.0
for smart cities

Final project brochure
Results

FFG
Promoting Innovation.

European Commission

Electric Mobility Europe

www.trolleymotion.eu

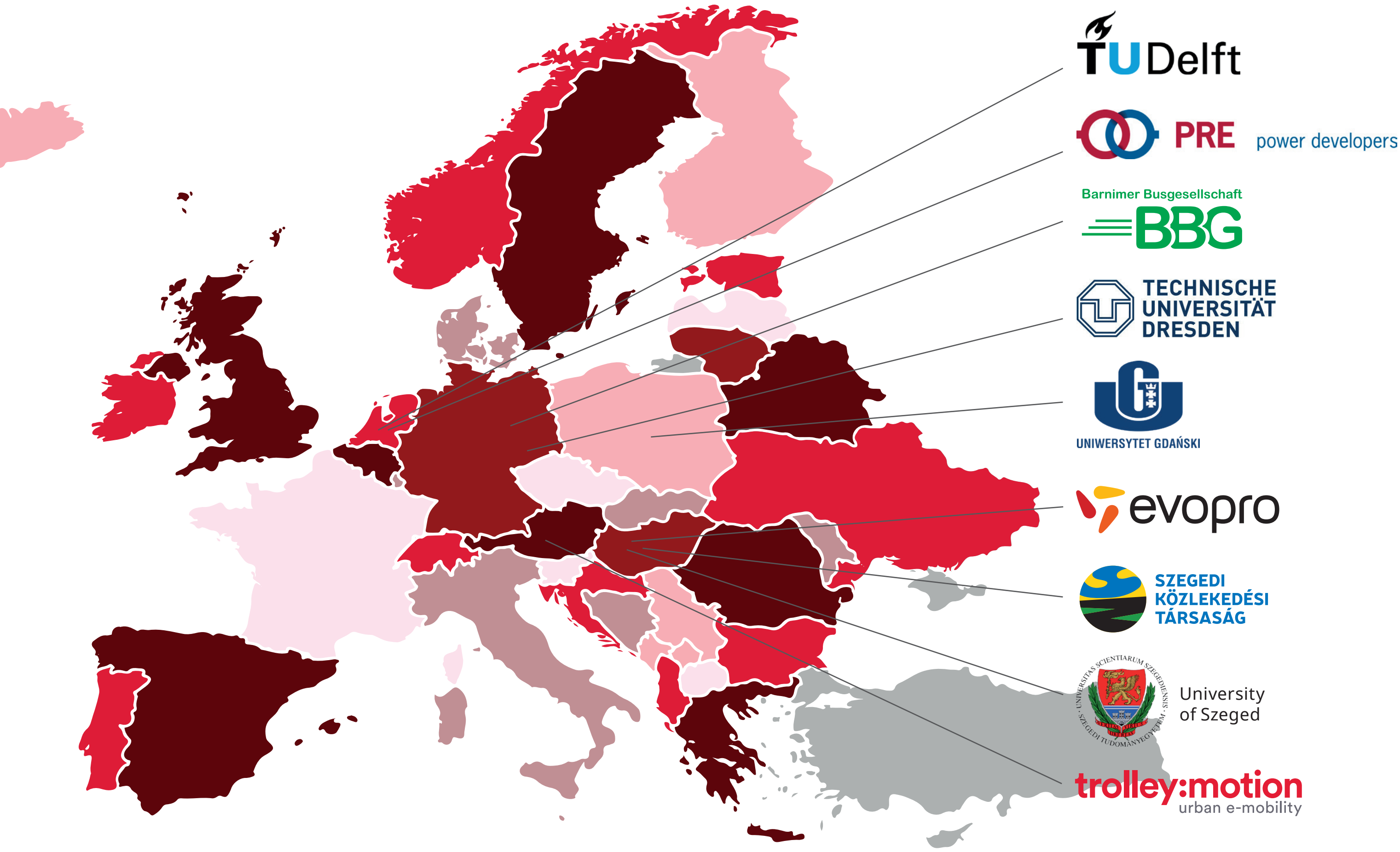
Consortium

trolley:2.0 team

The trolley:2.0 consortium is composed of 9 partners from 5 EU member states and includes the experience of 2 public transport operators, 2 industry partners, and 4 research partners. Further city authorities and public transport operators are involved as associated partners to enable industry and research partners to demonstrate new innovative solutions for electric public transport in their trolley networks.

trolley:2.0 in brief

The project started on the 1st of April 2018 and was completed in September 2020 with an overall budget of 3 million Euro. This project has received funding from the ERA-NET COFUND Electric Mobility Europe (EMEurope).



Associated Cities

Salzburg AG | AT
Stadtwerke Solingen | DE
City of Arnhem | NL
BKV Budapest | HU
MPK Lublin sp. zo.o. | PL
PKT Gdynia | PL

User Forum

Hordaland AG, Bergen | NO
Municipality of Maribor | SLO
Berliner Verkehrsbetriebe (BVG) | DE
OSY S.A. Athens | GR
Pilsen city transport company | (CZ)
TPER SpA, Bologna | IT
Verkehrsverbund Klagenfurt | AT
Verkehrsbetrieb Zürich | CH
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European Commission

Electric Mobility Europe

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FFG
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The research leading to these results has received funding from the Mobility of the Future programme. Mobility of the Future is a research, technology and innovation funding programme of the Republic of Austria, Ministry of Climate Action. The Austrian Research Promotion Agency (FFG) has been authorised for the programme management.

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Preface

Dear Trolleybus Community,

public transport is experiencing difficult times due to the worldwide Covid-19 pandemic. The fear of infections is leading to enormously declining passenger numbers and a rather restrained use of subways, trams and buses. This poses a huge challenge to the public transport sector. There are worries that individual car traffic could emerge from this crisis as the big winner.

Yet the challenges in this crisis can become opportunities! The public sector has shown that it is able to maintain its services as a reliable and inclusive means of sustainable transport. Also in order to achieve the climate protection targets of the Paris Agreement and the EU by 2030 and 2050 respectively, public transport needs to be an even stronger backbone for sustainable mobility systems in our cities and regions. Government authorities and mobility planners in our cities must stick to their long-term goals for the development of sustainable mobility systems and further strengthen the positive developments during the crisis, e.g. the increasing use of bicycles, and supplement them with a modern public sustainable transport system.

With the upcoming decade to 2030, the ambitious goals of the Green Deal and the implementation of the Clean Vehicle Directive are providing important push factors from the European Commission for us, and we are glad that the trolleybuses will be part of this movement. As trolleybuses are considered as clean vehicles or even zero-emission vehicles if equipped with a battery and thus capable of in-motion charging.

To this end, we worked together with our project partners over the last three years in the trolley:2.0 project developing solutions for energy-efficient and smart trolleybus systems. We proved that modern trolleybus systems can build such a strong backbone, needed for zero-emission public transport systems in European cities: Including concepts of in-motion-charging, as a central element of a smart and sustainable trolley network, and innovative solutions for shared and multi-purpose charging infrastructure, lightweight-constructions of a new midi-trolleybus type, automated wiring technology, concepts for the integration of renewable energy sources and tools for advanced cost-benefit-analyses.

With this brochure we are highlighting our major outcomes and deep insights of the project. We summarise our research and demonstrations' outcomes and provide lessons learned during the project lifetime.

Enjoy reading!

Yours

Wolfgang Backhaus, President trolley:motion

trolley:2.0 in a nutshell

Trolleybus systems provide modern, zero-emission public transport for urban areas, however, lack the flexibility that battery-equipped electric buses provide. trolley:2.0 combined the advantages of both systems, developing trolleybuses further into hybrid-trolleybuses that allow for the partial off-wire operation while making more efficient use of the trolleybus catenaries to charge the batteries in-motion.

The nine trolley:2.0 partners from **public transport, industry and research aimed to prove that battery-supported trolleybuses are a way forward** towards electric public transport systems in European cities by demonstrating the new charging concept in-motion charging (IMC), that allows for the partial off-wire operation of hybrid-trolleybuses in remote sections of the networks.

The trolley:2.0 use cases were located in four cities with existing trolleybus systems from different EU-countries, Szeged (HU), Arnhem (NL), Gdynia (PL) and Eberswalde (DE). Efficient public transport, flexible operation, and simplified extension of trolleybus networks as well as the combined use of the existing trolley grid infrastructure for further electrification of mobility in cities were actively supported by trolley:2.0.

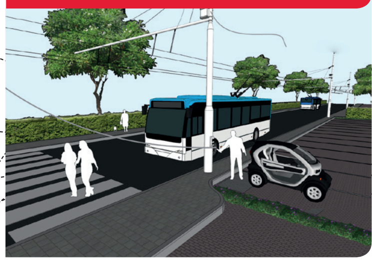
This brochure contains the main lessons learnt, barriers and drivers. The project results were systematically assessed in order to develop recommendations on how to successfully support the implementation of (IMC-) trolleybus-systems in your country or city.

Overview of trolley:2.0 innovations

Automatic Wiring and De-Wiring Systems

Source: DiaLOGIKa

Multi-purpose Charging Infrastructure



Smart trolley grid, Fransen TS

Integration of Renewable Energy

Direct charging of electric cars with photovoltaics, TU Delft

Buffer Stations and Energy Storage Systems

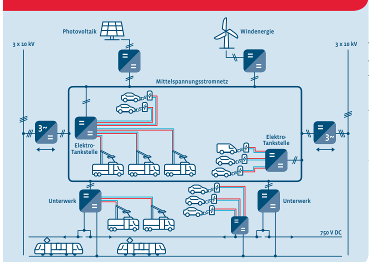
Source: Electroline

In-motion charging system, Kiepe Electric

New Trolleybus Operation Models: Feeder Bus Systems

Source: Evopro midi-bus prototype

Smart Grid Concepts



Source: ELIPTIC, Prof. Müller Hellmann

Zero-emission Public Transport

Source: ZeUS Poject, TMB

Quick facts: IMC-Trolleybuses

Suitability of IMC trolleybuses

In-Motion-Charging (IMC) trolleybuses have significant advantages over conventional battery-electric buses or conventional trolleybuses. IMC-buses can be equipped with smaller batteries and consequently are comparably low weight vehicles. Furthermore, they have the possibility to be operated continuously. IMC-trolleybuses are therefore especially well-suited for routes that have the following characteristics:

- long (no need to recharge en-route, or long unproductive recharging times at terminal stations)
- hilly (the external supply of energy allows for lighter vehicles, operating in a more economic and ecologic way)
- with high demand (IMC allows for double-articulated vehicles even under difficult conditions)
- with high frequency (which enables the investment in long routes) or any combination of the above. [1)]

When applied to a bus network, the choice of IMC is particularly attractive for routes that share several common sections. The more sections in the catenary grid are shared throughout the bus lines, the faster the upfront investment into the overhead wires is paid back.

[1)] *Knowledge Brief (draft version): "Infrastructure for introducing a new In-Motion-Charging System", October 2020*

Catenary Infrastructure

On the one hand, IMC allows buses to load their batteries without stopping while connected to the overhead line, on the other hand, the battery allows the bus to leave the overhead network.

With this feature, the electric infrastructure can be cut down to approximately 50% (and up to 30-40% under perfect conditions), for trolleybuses to still serve on the respective bus line. According to simulations and calculations performed in the context of the trolley2:0 project the infrastructure should not be reduced below 30% of the route length.

Even though in some cases, the share of electric infrastructure to route length was still be considered feasible around 25%. With the reduction of electric infrastructure, the amortization time for a trolleybus system is significantly lower since investment costs are drastically reduced. The more trolleybuses use the same infrastructure, the more efficient in terms of energy and economics the system becomes, since the costs are spread over multiple vehicles.

Total Cost of Ownership

Battery-trolleybuses are economically efficient on demanding lines with high passenger capacities, higher frequencies and daily driven kilometres and difficult topography. On these lines, the hybrid-trolley offsets initial investment costs through lower energy costs and in some cases is even cheaper than a Diesel bus.

These conditions exist especially in cities on central lines, connected to transport hubs such as train stations. Other operational parameters, such as the time spent at end stops, could also lead to an improvement of the total costs, as less infrastructure needs to be built along the route. The IMC concept is especially efficient when new lines are integrated into existing trolley networks. Once a core network is available, other lines should be investigated for electrification.

Batteries in In-Motion-Charging Trolleybuses; smaller Batteries, lighter buses

IMC-battery-trolleybuses are generally lighter than purely battery-electric buses. Since the major part of the route is driven below the catenary grid, only a small part must be operated in battery-mode. In comparison to battery-electric buses the conflict between having a very big (and heavy) battery on board, to last through the day or to have to make extensive stops, to charge the smaller battery and meanwhile losing valuable operating time, is radically less restrictive for battery trolleybuses. Smaller batteries make IMC-battery-trolleybuses lighter, than battery-electric buses.

Therefore, they are more optimal for economic and ecological driving on hilly roads. A feasibility study conducted in the Horizon 2020 ELIPTIC project [2)] as shown that it is feasible to convert existing Diesel bus lines in Eberswalde, Germany, to emission-free lines using battery-trolleybuses. The 910 line is a retrofitted battery-trolleybus line that charges under the existing catenary in Eberswalde and services the neighboring city Finowfurt using only traction batteries. The battery is mounted right where the Diesel engine used to fit, since both elements are comparable in size. The slot where the Diesel engine used to be is shown in the left picture, the right picture shows the mounted battery after the successful retrofitting.

[2)] *https://www.eliptic-project.eu/*

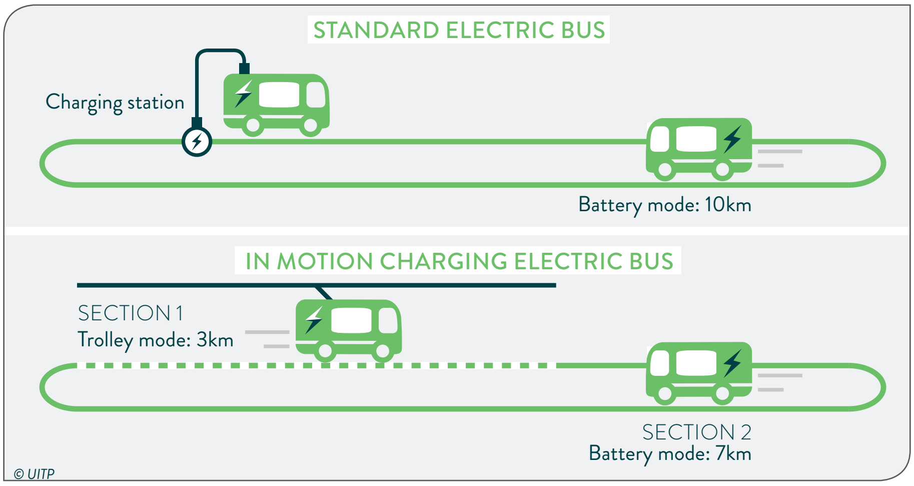
Gentle charging of batteries

Since IMC battery-trolleybuses are not dependant on charging as fast as possible like a battery-electric bus charging on a terminal, the charging power from the catenaries can be lowered most of the time. A lower charging power is generally better for the durability and lifetime of the on-board batteries.

Lithium-Ion Technology

A significant advantage of the in-motion charging technology is the possibility of having batteries with smaller capacity. As a result, the purchase costs can be decreased, as well as the weight of the vehicle.

The use of lithium-ion traction batteries for trolleybuses has significant advantages and allows for more flexible planning of the charging strategy. Apart from a significantly lower negative impact on the environment, lithium-ion batteries are characterised by having no memory effect, no dendrites which lead to internal short circuits of the battery cell. Among the main advantages of the lithium technology is the fact that the batteries have more than twice the energy density, which allows the installation of a battery with twice the capacity of the same weight.



Source: UITP Knowledge Brief: IN-MOTION-CHARGING - INNOVATIVE TROLLEYBUS, May 2019: https://cms.uitp.org/wp/wp-content/uploads/2021/01/Knowledge-Brief-Infrastructure-May-2019-FINAL.pdf

How to successfully implement (IMC-)trolleybus-systems and foster transition towards smart trolley grids

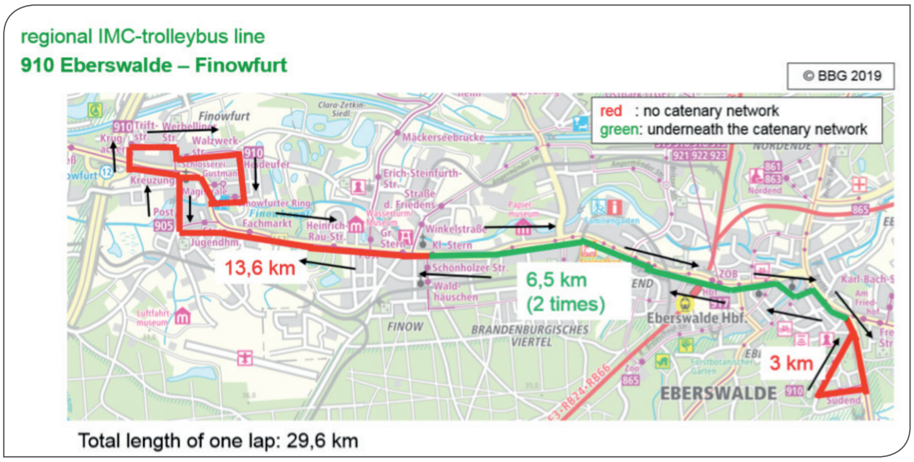
STEP 1: Going off-wire and gaining enhanced flexibility through in-motion charging (IMC) capabilities

Use Case: In-Motion Charging in Eberswalde (DE)

The bus network of BBG Eberswalde, Germany, covers a far larger area than the city of Eberswalde itself with 94km^2 and 40,000 residents. Instead, Eberswalde is integrated into a regional bus network covering numerous towns and cities in the northeast of Berlin. In contrast to entirely urban bus networks in densely populated cities, regional bus lines are characterized by long, continuous driving distances and low demand.

Owing to these parameters, buses in regional operation are principally Diesel-powered and electrification would present a major challenge. In Eberswalde however, trolleybuses have operated two inner-city bus lines for decades, meaning that there is an existing catenary grid on the trunk routes.

With the goal to replace Diesel buses not just in the urban but also in a regional context, Eberswalde utilizes in-motion-charging technology and its existing catenary grid to charge buses that operate on battery traction outside of the city.



Source: Barnim Bus Company
The use of In-Motion Charging battery-trolleybuses changed the use of trolleybuses radically in Eberswalde. The green line shows where on the route the bus goes under a catenary wire and proves how much more flexible an IMC battery trolleybus can be operated, when fitted with a battery.

Partner Quote BBG:

"The trolley:2.0 project has shown us that the trolleybus can very well be a future-oriented solution for public transport."

Frank Wruck, Eberswalde

Use Case: Szeged (HU)

The Szeged use case's objective is to prove that battery-trolleybuses are the proper technology for the extension of trolleybus networks and the replacement of Diesel bus lines in remote areas. Furthermore, Szeged put an existing composite frame midi e-bus/ trolleybus prototype into service. Within the trolley:2.0 project the Szeged Transport Company (SZKT) developed – together with the local manufacturer "evopro" – a prototype midi-battery-trolleybus with longer range and lower energy consumption.

Source: SZKT

To take the right decision on battery technology for the newly developed midi-battery-trolleybus, the trolley:2.0 project partner University of Szeged conducted a market research for usable cells, batteries, and modules. After collecting scientific and other technical publications, they reviewed the technical parameters of 44 battery types. According to the description of the task, most of them have lithium titanate oxide (LTO) and lithium nickel-manganese cobalt oxide (NMC) cells. The most important technical parameters are:

- *the battery technology,*
- *specific energy and specific power by weight and volume,*
- *constant and maximum power,*
- *charge power,*
- *number of charge / discharge cycles,*
- *module dimensions,*
- *charging and discharge temperature range,*
- *cooling and type of heating.*

Due to limited transparency of most battery products, SZKT had to take a decision on a reduced database. Eventually, they chose batteries with nickel-manganese cobalt oxide (NMC) cells, which fits the operating conditions in Szeged best. Based on higher capacity, performance, and lower price, SZKT finally chose to install NMC battery modules in their midi-battery-trolleybus.

Quote SZKT, Szeged:

"The trolley:2.0 project participation gave us important insights in hybrid trolleybus technology, regarding scaling of the batteries, charging powers as well as composite bus technology. This will be useful for future extension of the trolleybus network without infrastructure development using battery-trolleybuses."

Dr. Zoltan Adam Nemeth

Quote University of Szeged:

"Through the cooperation, we were able to get involved in a new form of trolleybus transport. We have been able to build valuable industrial relationships in the fields of bus manufacturing, transportation and battery manufacturing. In addition to the experience of analyzing the data collected in traffic, the experience gained during our measurements on battery modules and cells is very valuable for our future research."

Dr. Istvan Peter Szabo PhD

Use Case Gdynia (PL): costs and influences on the development of In-Motion-Charging

Gdynia is a medium-sized city located on the Baltic Sea in northern Poland. It is an element of the core of the Gdańsk-Gdynia-Sopot Metropolitan Area, which includes 57 communes. Currently, Gdynia has a population of 246,000 and together with Gdansk, Sopot and other communes forms the Metropolitan Area of Gdansk-Gdynia-Sopot, being one of the most important urbanised areas in Poland. The motorisation index in Gdynia amounted to 602 cars per 1000 inhabitants in 2018 and was 84% higher than in 2004. Gdynia is no exception, and this trend was and is a characteristic feature of the whole country.

In the trolley:2.0 project the project partner University of Gdansk refined a model to compare the costs of (battery-)trolleybuses, battery-electric buses and Diesel buses. For this, 11 key performance indicators (KPIs) were developed. KPI categories were operation, energy, economics and battery. Thanks to the use of the KPI framework, it was possible to reduce the differences in the size of trolleybus systems to a standard analytical level. This made it possible to find an answer to the research question: "Which factor(s) have the most significant influence on the development of in-motion charging technology in trolleybus transport?"

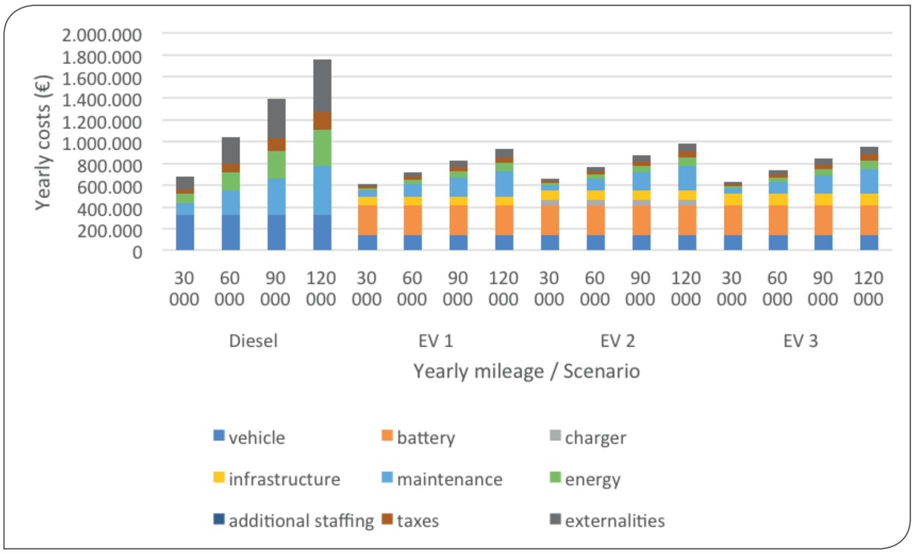
To verify the efficiency of trolleybus network development, a lifecycle cost model was created, as part of the previous TROLLEY project (funded in the Central Europe Interreg programme (2010-2013), extended and developed within the Horizon 2020 ELIPTIC project (see above) and adjusted to specific conditions for Poland within the trolley2:0 project.

The model is easily adjustable for local conditions and issues. It has been updated for this analysis to include the following variants for a public transport line:

1. Diesel bus service;
2. 'classic' trolleybus service with network construction costs along an entire route and without batteries;
3. BEVs with mixed and overnight charging – the most promising BEV solution in most cases as – among others – shown by the ELIPTIC project findings because of the optimal trade-off between battery costs and operational capabilities resulting from the battery capacity;
4. Battery-trolleybuses charged from overhead trolleybus networks – IMC trolleybuses or so-called 'trolleybus without catenary' – a solution that can be used only in cities with existing trolleybus infrastructure that run buses along the trolleybus network to connect to stations with no existing overhead network. In these cases, although BEVs may be introduced without investment in infrastructure, vehicle costs increase due to the battery component. As well, overhead networks were slightly increased, resulting in some additional costs.

Taking into account the cash flows of operators, classic trolleybus service – in which full network construction costs must be covered – often is not a competitive solution. Using battery-trolleybuses (4) charged from an existing overhead network as a complement is an optimal solution for typical services.

Using an existing trolleybus network instead of financing new chargers moves the break-even point against Diesel buses from approximately 270 km/day to about 190 km/day, meaning BEVs are recommended for all but typical peak service. The difference in total costs between variant (1) Diesel, (3) BEV is nevertheless very slight and amounts in case of high mileages 0,17€/km, and in case of medium mileages – 0,09€/km, both in favour of variant (3). Classic trolleybuses (2) increase costs compared to Diesel (1) respectively by 1,08€/km and 0,60€/km.



Source: University of Gdansk
The Figure shows the economic cost structure for Gdynia: *(Diesel) Diesel bus service; (EV1) 'classic' trolleybus service with network construction costs along an entire route and without batteries; (EV2) BEVs with mixed and overnight charging; (EV3) BEVs charged from overhead trolleybus networks – in-motion charging trolleybuses or so-called 'trolleybus without catenary'.*

A key factor determining the development of trolleybus transport using in-motion charging technology is progress in the development of traction batteries. The noticeable increase in average battery capacity is accompanied by a change in the generic structure in which NMC and, to a lesser extent, LTO batteries predominate.

The high upfront costs of purchasing modern trolleybus vehicles could be regarded as one of the most important barriers in a quick technological development of traditional trolleybus systems. The cost of a 12-metre hybrid trolleybus (equipped with a battery) is twice as high as the cost of a standard Diesel bus that complies with the EURO6 norm. However, it needs to emphasised that trolleybuses have a longer life cycle of over 20 years. In-motion charging technology leads to a development of trolleybus transport and has a qualitative dimension primarily and is expressed in the possibility of at least maintaining the current level of operational work, as well as in the creation of new options for the spatial expansion of trolleybuses into areas without catenary. The environmental effects of electric traction in transport are strictly dependent on the method of primary energy generation.

Whether In-Motion-Charging battery-trolleybuses are a development depends on the point of view and the sources of Energy. First, the share of renewable energy sources must be increased to achieve a positive impact from the ecological point of view. However, the time to cancel Diesel buses has not yet come, when seen from an economic point of view. In the meantime, we must work on cheaper electric buses, charging infrastructure, as well as electricity. When establishing In-Motion-Charging the project partner from Gdynia recommends focussing on single lines, instead of the general system and to minimize the battery capacities on these lines. At the same time the existing or planned infrastructure must be used as much as possible.

Source: PKT Gdynia

Quote University of Gdansk:

"trolley:2.0 has created a platform of collaboration between public transport operators, cities and scientists. Such an environment, full of ideas and practical developments inspired us towards new IMC trolleybus deployment concepts."

Dr. Marcin Wolek

STEP 2: Becoming truly green: turning your trolleybus network to smart, energy-efficient and zero-emission trolley grids

Use Case: Arnhem (NL) and the integration of renewable energy sources

The municipality of Arnhem (NL) has the ambition to be a global leader in trolley grid technology and be the world's first city with a truly smart trolley grid. Arnhem also wants to become an "energy city", for which a smart trolley grid is indispensable.

These two ambitions come together within the trolley:2.0 project and demonstrating the potential of trolley grids to become DC backbones for battery-electric vehicle charging, integration of photovoltaic energy, break energy recuperation for trolleybuses, as well as installation of stationary energy storage.

The integration of renewable energy sources, such as solar or wind power can be achieved in multiple ways. At a first glance, the integration of PV seems to be the favourable choice of renewable energy for the following reasons:

1. Both the PV panels and the catenary grid for trolleybuses are DC systems. By connecting the PV directly to the DC system, one fewer converter is needed. This reduces transmission losses and component costs.

2. The diurnal variations in PV are closer to the busload profile than those of wind energy. On the other hand, the wind generation better matches the bus demand on a seasonal level. The PV system anticipates less power dump on a daily basis than a wind energy system.

3. Diurnal bus demand variation on the grid.

4. PV system are better scalable than wind turbines to system sizes at the order of the substation demand of tens or hundreds of kWs. The PV system can be easily distributed at the substation level. The result of this is lower transmission losses and a distributed footprint of the system.

Source: Kiepe Electric

However, even though PV seems to have significant advantages, there are multiple ideas to implement renewable energy sources in the catenary grid. The following four scenarios describe some of the different approaches more in detail:

Scenario 1: decentralized, energy-neutral, PV utilization and dump in the MVAC grid

The ideal scenario for PV integration is to size the PV at each substation, so that it provides the total energy demand of that substation per year. The grid is then fully sustainable. By the end of the year, its net exchange with the grid is zero, making it energy-neutral. Additionally, the generation in this case is near the load, reducing the transmission losses. But, this first scenario has major concerns. The first is the large footprint of the PV in the busy parts of the city (where there already is an inherent lack of space). The other problem is the large dump into the MVAC grid. The PV Utilization for the trolleybus-catenary-grid is as low as between 15%-38%, meaning that the dump into the MVAC grid is from 62%-85%. Such systems dumping large portions of their power into the grid can have serious consequences on the grid's stability and power quality. The problem of PV Utilization comes from several factors, such as the traffic (presence of a bus), bus load demand, bus scheduling (night bus demand), substation voltage, presence of bilateral connections, section length, etc.

Scenario 2: high traffic substations, PV and optimal dump

Traffic is one of the key curbing factors for the PV utilization. The second scenario investigates the placement of PV only at the high traffic substations. An optimal-dump sizing is suggested. This optimum is defined as the size at which the marginal PV dump exceeds the marginal PV direct utilization. In simpler terms, it is the size, beyond which if the PV system is increased by 1kW, it would dump more of this added 1kW than it would directly use. For most substations, the suggested size is then 0kW, meaning a negative advice toward placing a PV system. In Arnhem, only five substations have a suggested positive PV size under this approach. Being selective with the PV-powered substations would only cover a small powering of the bus demand. In this case, 8% of the yearly grid demand. Oversizing these stations and wasting the excess power is not a feasible solution either. Storage is a necessary addition if higher green energy fractions are requested. A study of an aggregated approach offers even better solutions.

Scenario 3: Centralized Wind, Energy Storage System

For an energy-neutral grid, an exemplary energy utilization of 80% of the trolley grid, requires the large size of 100MWh of storage. The bus mismatch with wind, although reduced seasonally, still is very pronounced on a daily level. A logical conclusion is then to integrate a hybrid system of PV and Wind.

Scenario 4: Centralized PV and Wind, Energy Storage System

The bus suboptimal matching with renewable energy sources, can be reduced on a daily and seasonal level with a hybrid system of PV and wind, which uses the matching advantage of both. The fourth scenario analyzes the performance of an energy-neutral hybrid solution, and indeed, a hybrid solution of PV and wind of about 50% each seems to be the best outcome with 54% direct utilization. This utilization factor can be pushed as high as 80% with only 30MWh of storage. While this storage value is still significant, it is much smaller than what is required for a PV system alone to reach such a utilization value (500 MWh) or for a wind system alone (100 MWh).

STEP 3: Become a backbone for e-mobility applications: enable the multi-purpose charging of other electric vehicles from your trolley grid

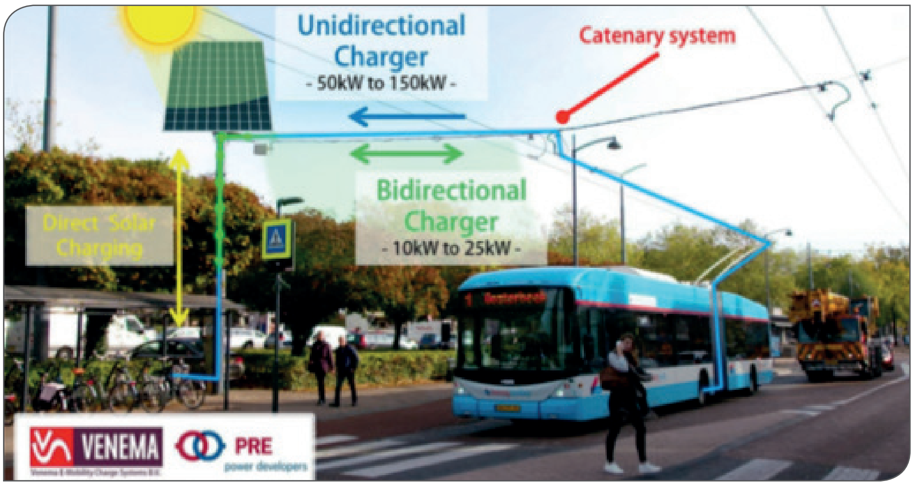
Multipurpose use of smart trolley grids

Sparked by the current trend to transform existing trolley grids into smart trolley grids (i.e. integrating multipurpose use, brake energy recuperation, bidirectional converters, stationary energy storage, renewable energy sources, etc.) and fading borders between battery-electric and trolleybuses, new use cases for the existing infrastructure of trolleybuses are being explored in cities throughout Europe and the world. It is expected that electricity demand in urban areas will grow substantially due to increased use of electric vehicles. New charging solutions need to be generated to supplement electricity grids locally. Furthermore, DC fast-charging hubs are especially important in cities to enable EV take-up without requiring too much parking capacity. The readily available DC infrastructure of trolleybus traction grids could display a cost-efficient solution.

There are many use cases for multipurpose public transport infrastructure. Exemplarily, the options of using power grids of light rail or trolleybus networks to charge technical support vehicles, battery-electric buses, and electric vehicles of an on-demand mobility service have recently been tested in London (UK), Prague (CZ), and Arnhem (NL) respectively. In Arnhem, a flexible on-demand service to supplement and extend regular public transport in the southern Gelderland region of the Netherlands, was in trial operation for three years, completing around 125,000 journey per annum.

This pilot was enabled by innovative multipurpose chargers drawing power directly from the DC trolley grid:

Source: VENEMA; Fast charging from a (DC) trolley network



Source: VENEMA/PRE Power; trolley:2.0: Concept drawing of multipurpose charger

The inclusion of EV chargers in the trolley-grid can be beneficial in multiple ways. The installed vehicle Fast-Charger is an all-in-one combination for the charging of electrical vehicles. It is powered by the DC Trolley-tram network. Since the system is DC-DC it has less energy loss than traditional charging systems. Electric vehicles can be charged in a sustainable way.

Furthermore, the charging point does not require a connection to the traditional power network if it is connected to the trolley-tram-network. As a result, many cost factors can be saved that would occur for the connection to the power grid or the operation. This strategy improves the traction grid utilization and can also reflect positively on the Renewable Energy Sources Utilization by creating a base load for the renewable energy source rather than dumping into the grid.

While current legislation prevents public transport operators from selling energy from their power grids to third parties or for the purpose of private consumption, the Arnhem use case shows how trolley grids can used for multiple purpose internally. Especially trolley grids offer a wide range of applications fostering internal and, if legal, external synergies arising from the multipurpose use of the proprietary power grid. Trolleybus operators should start exploring new applications and business cases for trolley grids to become the new backbones of electric mobility.

Underutilized Catenary Grids in Arnhem and the grid of the future

In this context, the trolley:2.0 project carried out critical analyses proving the technical feasibility of an EV charging system drawing power from the DC trolley grid. Additionally, the project's scope included the use of brake energy from buses, stationary energy storage, and integration of photovoltaics in for public transport operators to reduce peak power demand, increase grid resiliency and become more energy autonomous.

TU Delft elaborated a vision of the Catenary Grid of the future. Moving away from the monofunctional grid, that could only be fed centrally and only be used by the trolleybuses, the Grid of the future includes decentralized power supply e.g., through PV and storages. In addition, the Grid of the future allows other electric vehicles to charge.

Last, but not least, trolleybuses charge their on-board batteries in motion (IMC) and are flexible to leave the Catenary Grid – either due to unexpected obstacles or to cover areas outside of the Catenary Grid. TU Delft aimed to minimize the use of (seasonal) storage and the AC Grid.

The overall aim is to achieve a 100% sustainable, energy neutral Catenary grid. The buses, like any transportation system, run on a schedule with some time interval in between them. The result is that a supply area in the grid, (especially in low traffic zones,) will experience long periods of no bus demand. The trolley grid infrastructure is then underutilized.

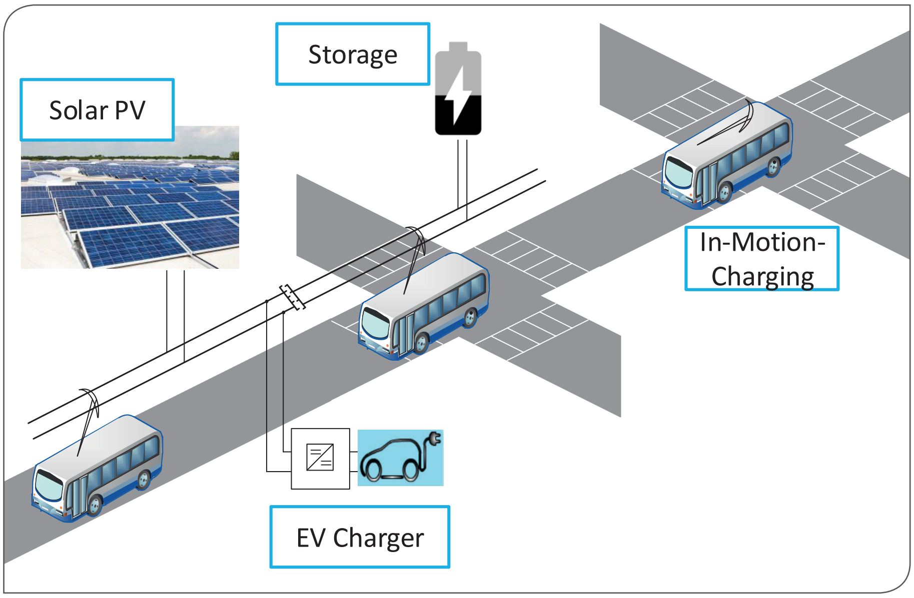
Moreover, as the trolleybuses run with the regular traffic, the trolley grid infrastructure is already oversized to cater for unanticipated bus load stresses. This is the case when buses are suddenly congested into one zone due to bus delays and/or traffic situations. In short, the state of the present-day trolley grid is the case of an oversized, underutilized, and mono-functional city-wide electricity grid.

The prospective of making it a more active part of the local grid is both possible and necessary. The emissions for feeding the current trolley grid are about 2000 tons of CO_2 per year. Arnhem therefore wants to integrate renewable energy sources like PV, integrate energy storage systems, integrate electric vehicle (EV) chargers and employ In-Motion-Charging Trolleybuses in their vision of the grid of the future.

TU Delft quote:

"To design the trolley grid of the future, it was essential to meet and work with many partner cities, allowing us to understand the status-quo of trolley grids across countries, and their practical strengths and challenges. Trolley2.0 facilitated this network-making and knowledge-sharing between academic institutions and trolley grid stakeholders, allowing us to feasibly orchestrate new directions from the current trolley grids. The steps that we are suggesting are futuristic and beneficial, but also concrete and realistic thanks to this international feedback pool. The connections we have made are solid and still active now, even beyond the final project conference."

Prof.Dr.ir. P. Pavol Bauer



Source: TU Delft

trolley:2.0 user forum city Pilsen (PMDP):

In the **city of Pilsen, Czech Republic,** a buffer energy storage station was installed to strengthen the trolleybus catenary network.

The charging station is completely independent from the power grid. It is only connected to the trolleybus overhead wires from which its battery is continuously charged, and under load it is able to quickly supply a larger amount of energy back to the trolleybuses.

Several different parameter options were tested to find the best settings of operation needs. Furthermore, different operation modes have been tested: the regular operation – the storage station was mainly balancing the voltage level, a turn-off or power-cut from the substation and a higher power consumption scenario, which included charging of the trolleybus batteries, the use of air-conditioning, etc.

This installation allows to find out where the weaknesses and the reserves are and at a later stage how to reduce electricity consumption.

Source: Buffer Storage in Pilsen (CZ), PMDP, EfficienCE project
https://www.interreg-central.eu/Content.Node/Press-release-3.html

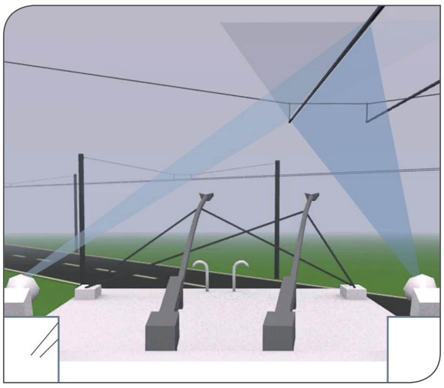
trolley:2.0 innovations

The innovations demonstrated by trolley:2.0 contribute significantly to improve the flexibility of trolleybus systems and will further strenghten the economic and operational competitiveness with other clean bus systems.

Automated wiring to the catenaries

Libroduct presented an automatic rewiring technology in the trolley:2.0 project. This is helpful when a battery-trolleybus must dodge an unforeseen obstacle. On the other hand, this allows the use of just one catenary wiring – for both driving directions. When two buses come towards each other, one shortly dewires and reconnects afterwards.

The rewiring is carried out automatically. The automated rewiring has been tested in the city of Szeged (HU) with an existing Skoda trolleybus. First real-life tests have been performed, and the software performs as expected, however, the hardware needs to be upgraded.



Source: above: LibroDuct, below: SZKT

Lightweight modular vehicle tested in Szeged (HU)

The project partners in Szeged developed a new midi-battery-trolleybus in the trolley:2.0 project. Together with the local manufacturer evopro the partners worked on a prototype with a longer range and lower energy consumption. They chose to work with the model "Modulo" – a modular structure, that can be assembled according to the ideas of the customer. Four to seven segments can be assembled to create buses, with different lengths and more importantly different capacities to transport public transport users. The team from Szeged decided to assemble a bus out of six segments, one for the driver and the front wheels, one for the rear wheels and in between two segments with doors and two regular middle segment. The advantage of this kind of bus is not only the flexibility and that it can be designed precisely as needed, but also the bus is comparably light weight. When fitted with comparably small batteries, because of temporary catenary grid use, this bus turns out to be very economically and ecologically efficient.

Source: evopro

European-wide take-up of innovations: the trolley:2.0 User Forum

trolley:2.0 User Forum

In the trolley:2.0 project city authorities or public transport operators were invited to join the User Forum. Cities that were interested in upgrading their trolleybus system and learning about challenges and opportunities of the introduction of battery-trolleybuses could apply to become members. In the User Forum the members could exchange knowledge about battery-trolleybuses and smart trolley grids. Different workshops, site visits and take-up activities were organized in this context.

The User Forum consisted of:

- Hordaland AG
- Bergen (NO)
- Municipality of Maribor (SLO)
- Berliner Verkehrsbetriebe (BVG) (DE)
- OSY S.A. Athens (GR)
- Pilsen City Transport Company (CZ)
- TPER SpA, Bologna (IT)
- Public Transport Klagenfurt (AT)
- Public Transport Zurich (CH)
- Marburger Verkehrsgesellschaft (DE)

In addition, all associated trolley: 2.0 partners participated in the User Forum. The User Forum Cities could benefit from an exchange of experience on the following trolley: 2.0 topics:

- In-motion charging concept for battery-operated trolleybuses
- Midi-hybrid trolleybus as a system to extend the existing trolleybus network to remote areas
- Testing automated wire-and-wire technologies
- Multi-purpose trolleybus networks enabling the charging of other electric vehicles and the integration of solar energy
- Stationary energy storage systems and intelligent energy management of trolleybus networks (e.g. optimized use of recuperation energy)
- Integration of 2nd-life batteries, bilateral energy supply, etc.

trolley:2.0 user forum city Berlin (BVG), Germany:

"Through our participation in the trolley:2.0 User Forum, we have learnt that Trolley-IMC busses are based on a reliable technology. Since the Berlin bus network is the largest in Germany, the network has a broad range of lines and services to be electrified. That is why BVG and Berlin need an integrated electric bus strategy with different zero emission technologies, and the exchange with the trolleybus community showed us that trolley-IMC busses could play a major role on our way to a 100% locally emission-free bus fleet by 2030."

Dr. Daniel Hesse

Source: BVG; trolleybus simulation in Berlin

Source: trolley:motion; Knowledge Exchange at the CIVITAS Forum 2019, Graz/Austria

The way forward: the trolley system of the future

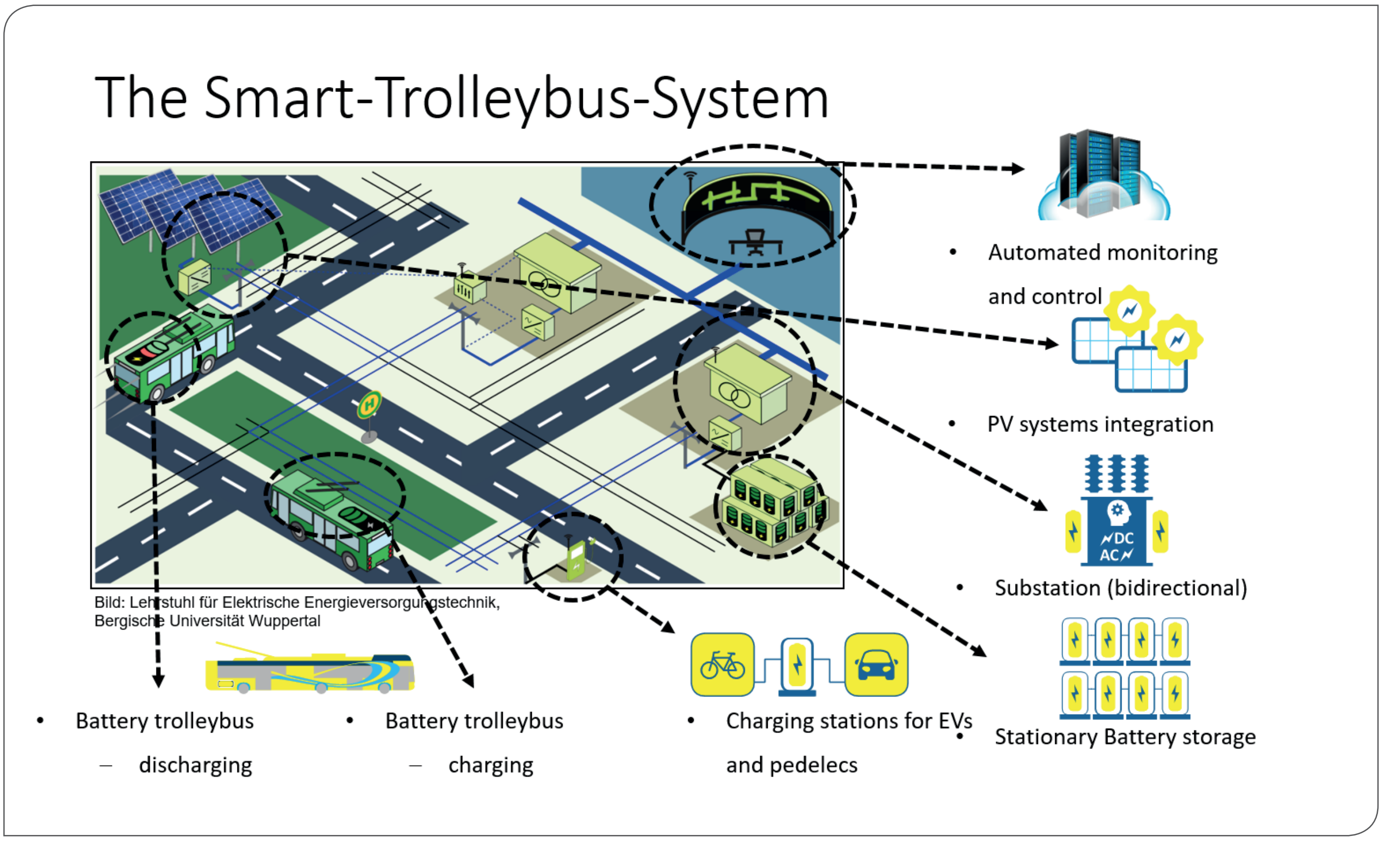
The trolley:2.0 user forum city Solingen (SWS), Germany, and the "BOB" project:

"A valuable opportunity to discuss our results on the acceptance analysis of smart trolley systems like the BOB with a European expert panel and to place them in the international context."

Adrian Dogge

As a vision for the future the User Forum City of Solingen follows a holistic approach around their catenary grid. The integration of multiple elements is planned. This includes:

- The integration of multiple entities,
- Simulating the electrical grid,
- Simulating the traffic network,
- Topography data for energy demand forecasts,
- Vehicle weight and passenger count



Conclusions

A general definition for battery-trolleybuses is indispensable

The Hungarian legal framework – which derives from UNECE regulations – identifies two distinct categories, trolleybuses: "a car connected to an electric overhead line" and buses: "a motorcar designed for the carriage of passengers, not connected to an electric overhead contact line, [...]". That leaves the question: What exactly is the hybrid trolleybus, that keeps the catenary on its route?

Recommendations:
Nowadays, despite countless functioning examples, battery-trolleybuses with IMC strickly do not fulfil the UNECE regulations! Each country do regulatory workarounds.

- The UNECE regulation 100 5.3 must be changed to allow IMC.
- UNECE regulation 100 5.1.2.3 should be adapted to hybrid trolleybuses with IMC

By merging the electric bus and the trolleybus category, the following results can be achieved:

- A **unified market** for IMC and trolleybus vehicles, instead of country-by-country rules. This would enable a second-hand market as well
- **Easing the regulations for the manufacturers:** no more separate testing and authorization requirements for trolleybuses between country-by-country, or between e-bus - trolleybus
- **Encouraging a choice and combination of charging infrastructure:** today heavy-duty electric buses usually combine overnight and opportunity charging (range extender). IMC could be used as a range extension, for example by running 10 % of the route under the catenary grid

Drivers and barriers for In-Motion-Charged battery-trolleybuses

Throughout the trolley:2.0 project, several drivers and barriers were identified.

The following four drivers would undoubtfully have a positive impact on the use of public transport in general, electric buses or battery-trolleybuses in particular:

1. A major impacting factor for electric buses in general is the technological advancement in batteries. Better batteries are either lighter, more efficient or store more energy, due to a higher energy density. All improvements would reduce the price per km and the total lifecycle costs and making electric buses more and more competitive compared to Diesel buses.
2. An EU policy that supports the transformation of transport systems towards zero-emission level would have a significant impact on the use of electric buses of any kind, i.e. decision makers should not neglect or ignore (IMC battery-)trolleybuses as means of a sustainable public transport system.
3. Investment opportunities in the catenary infrastructure would push the use of (IMC battery-)trolleybuses. Unfortunately. There is a lack of financing and funding programmes to invest in the catenary infrastructure.
4. A clear prioritization of public transport vehicles in traffic, i.e. bus lanes, would radically improve the attractiveness of IMC concepts and public transport in general.

On the other hand, the main **barriers identified** are the the high upfront costs for purchasing the modern IMC-capable vehicles and the often old-fashioned image of trolleybus technology, which can only be overcome by increasing the awareness of innovations around IMC concepts.

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