RIDING IN BUSSES THAT USE LITTLE ELECTRICITY

The electrification of local public transport is in full swing. Building battery-operated buses and trolleybuses that combine passenger comfort with low power consumption is technically challenging. Research institutions such as the Swiss Federal Institute of Technology (Eidgenössische Technische Hochschule/ETH) in Zurich are supporting manufacturers with important findings such as the optimal use of batteries, for example. A current research project aims to improve the energy supply for heating, ventilation and air conditioning.

The battery on the roof enables this trolleybus to travel routes without overhead power lines. Photo: B. Vogel

A technical report about the results of a research project in the field of mobility, which is financially supported by the Swiss Federal Office of Energy. The report has been published in the technical magazine Umwelttechnik (issue June 2023).

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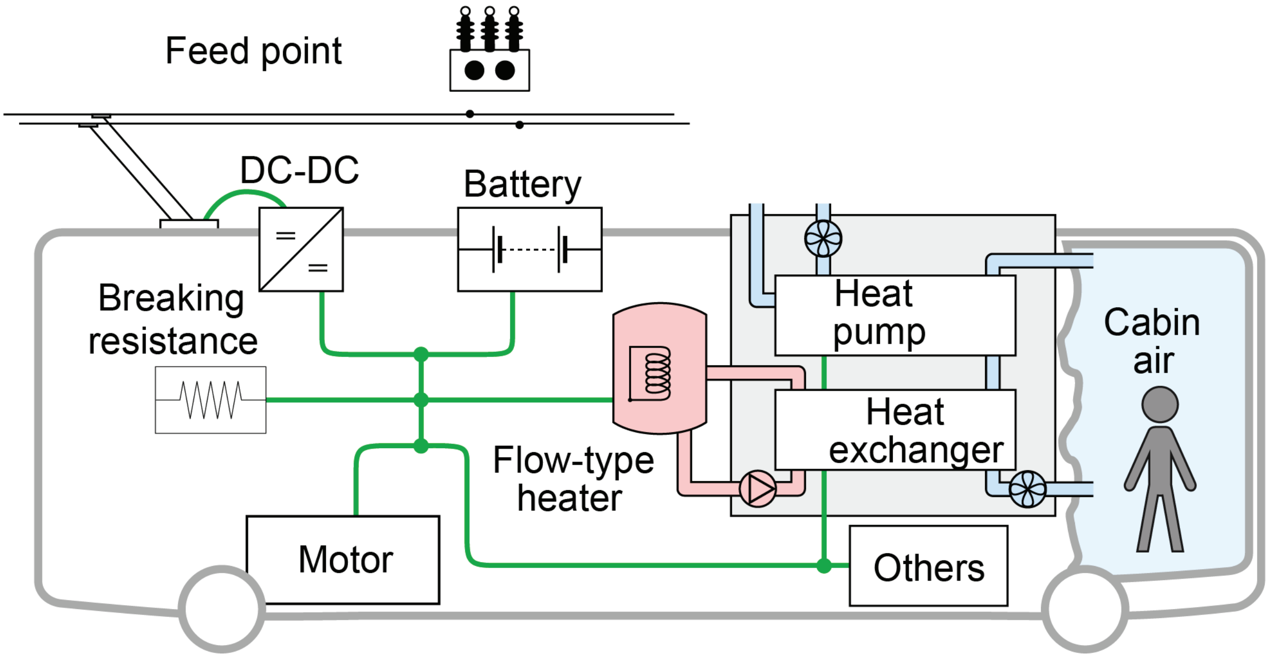
Diesel buses provide a considerable share of transportation needs in Swiss cities. But that is set to change: For climate protection, most transport companies want to replace fossil-fueled buses with electric alternatives such as trolleybuses and battery powered buses in the short and medium term. For electrification to succeed, high-performance electric buses are needed that meet the diverse requirements of urban transportation. "Research is also needed here, as good trade-offs between a wide range of target variables such as investment costs, energy efficiency, longevity, comfort, etc. can be achieved by using simulation and optimization tools as well as self-learning algorithms," says Christopher Onder, professor at the Institute of Dynamic Systems and Control (IDSC) at ETH Zurich.

A battery-assisted articulated trolleybus of the Verkehrsbetriebe Zürich. Photo: VBZ

Battery-operated trolleybuses

Researchers at the IDSC, for example, participated in the development of the "SwissTrolley plus." The project resulted in a trolleybus in 2019 that, thanks to a powerful battery, can also be used in areas that are only partially equipped with overhead power lines. In addition, thanks to the battery, the SwissTrolley plus can make better use of recuperated braking energy by temporarily storing it in the battery for later use. Researchers at ETH Zurich developed a self-learning energy management system for the bus to charge and discharge the battery. Compared with the previous generation of trolleybuses, around 15 % of the electrical energy can be saved.

Public transport buses must meet stringent requirements: They should run on time and without disruption. But they should also offer passengers a high level of comfort, including sufficient seating and storage space for luggage, as well as fresh and well-tempered air in the passenger compartment. To make passengers comfortable, heating provides warmth on cold days, ventilation ensures air exchange, and air conditioning cools on hot days. Heating, ventilation



Energy system of a trolleybus that, thanks to a battery, can also travel to areas without an overhead power line. An ETH study investigated, among other things, how the service life of the battery can be extended by clever charge/discharge management or by optimized operation of the heating system. Green stands for electrical connections, red for hot water, blue for air. Illustration: ISOTHERM final report

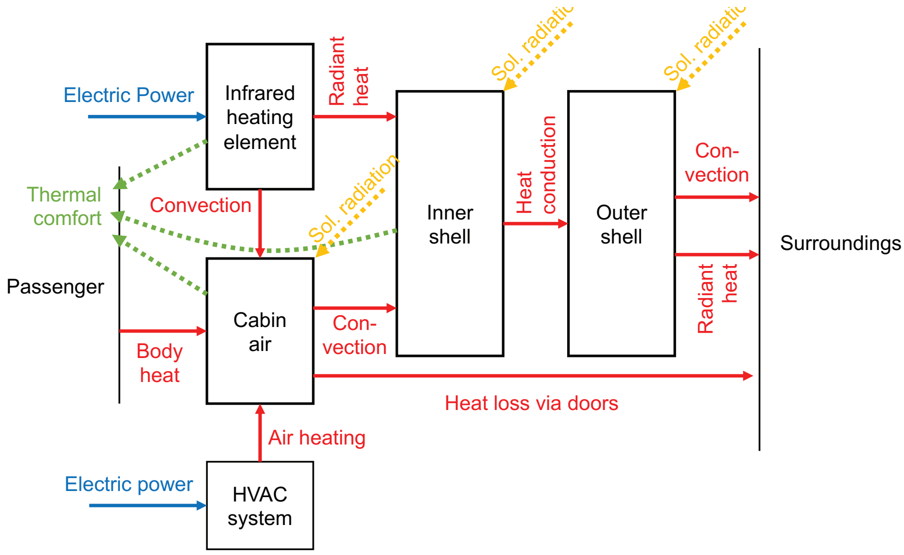


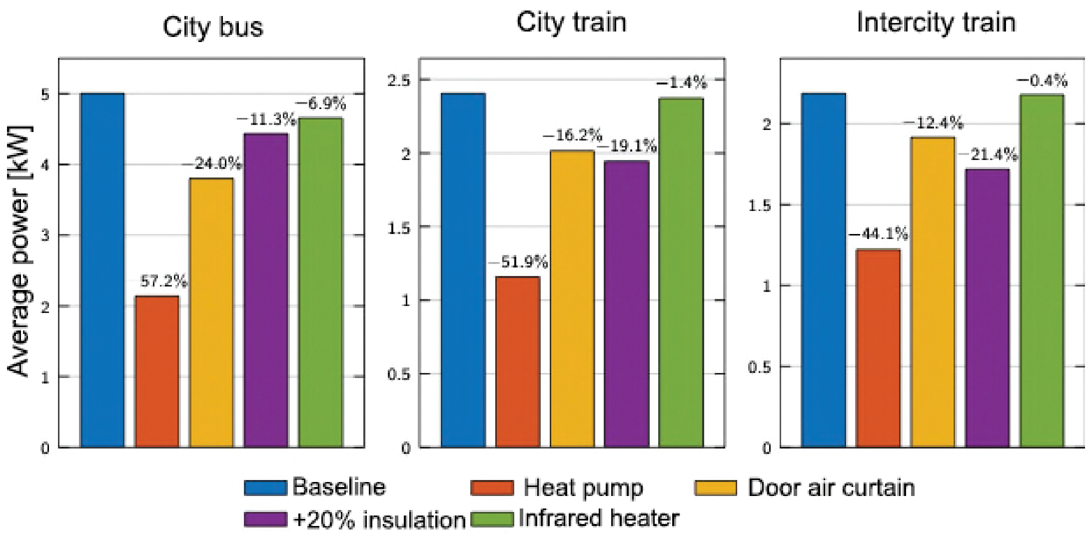
Illustration of the simulated heat flows in a public transport vehicle according to the model developed by Fabio Widmer at ETH. Illustration: Final report ISOTHERM

and air conditioning (HVAC) systems account for a significant share of bus energy consumption: On cold winter days, they sometimes consume as much or even more electricity than the drive system.

Waste heat from the engine is missing

Energy supply for the HVAC systems poses a particular challenge for battery-powered buses. In diesel-powered buses, energy for heating can largely be obtained from the waste heat of the engine. In electric vehicles, this energy source is not available because the (very efficient) drive components have very little heat loss. The energy to operate the HVAC systems must therefore be drawn from the battery. This in turn reduces the range of the vehicles.

The design and control of the HVAC systems of electrically driven vehicles is therefore an important technical challenge. ETH scientist Fabio Widmer searched for optimization possibilities as part of his doctoral thesis. His findings apply to various electric vehicles, including not only battery-powered buses and trolleybuses, but also streetcars and rail cars. Widmer recently completed a study titled Intelligent Software for Thermal Energy Management (ISOTHERM). The Swiss Federal Office of Energy co-financed it with funds from the Mobility



The graphic shows how much the energy consumption of HVAC systems can be reduced on average, annually, by implementing four different efficiency measures according to the ETH study (each case was compared to an HVAC system with classic air conditioning and electric heating). The highest reduction can be achieved by using a heat pump in electric buses as well as in commuter trains or intercity trains. In modeling these consumption values, the assumption was made that the PMV value (cf. explanation in the text box p.4) must not be below -1 in winter (passengers perceive the indoor climate as slightly too cool on average) and not above +1 in summer (passengers perceive the indoor climate as slightly too warm on average). Graphic: Fabio Widmer research program. Further support was provided by the bus manufacturer Carrosserie HESS AG (Bellach/SO). Verkehrsbetriebe Zürich (VBZ) provided one of its trolleybuses for field trials.

Heating and battery aging

One focus of Widmer›s scientific work was the question of how to reduce battery wear (degradation) in battery-assisted trolleybuses. The ETH researcher developed a heating control system that avoids strong discharging and charging currents, thus conserving the battery. This goal is achieved by operating the heating system with recuperation energy whenever possible, i.e., with the electricity that is generated when the bus brakes. In this way, the charging currents of the battery can be reduced. Conversely, during phases when the bus is accelerating with battery power, heating is forgone. In this way, strong currents can be avoided when discharging the battery.

When controlled in this way, the bus heating system is no longer permanently in operation. However, this does not lead to a loss of comfort, since the temperature in the bus drops only very slowly when the heating is temporarily inactive. The ETH scientist›s novel control system was tested in practice in the last quarter of 2022 in a battery-assisted trolleybus operated by the VBZ. The aging of the battery was reduced by 12% during this time. In other words, thanks to the new control system, batteries have a significantly longer lifetime, which is also financially beneficial.

Heat pumps save up to 60 % energy

Most of the results of the ISOTHERM study are not based on field measurements, but on model calculations. For this purpose, Widmer developed a model that can be used to describe the indoor climate in buses, streetcars or train cars. The model takes into account various variables: type and capacity of heating and cooling, thermal insulation of the walls, air exchange when the doors are open, heat input from the sun, outside temperature, but also heat dissipation by the passengers. The model can be used to calculate possible indoor

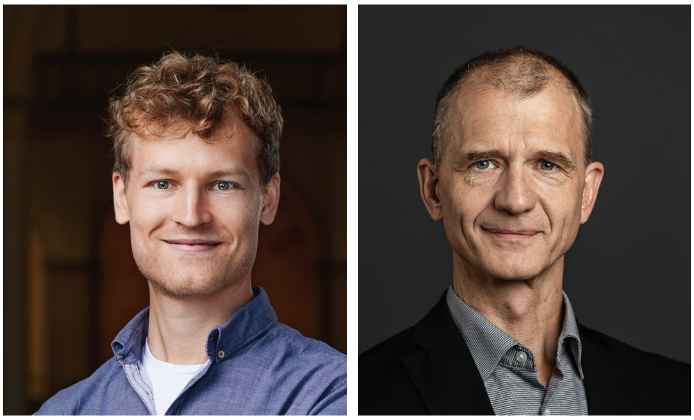
THERMAL COMFORT IS MORE THAN JUST THE RIGHT TEMPERATURE

The aim of heating, ventilation and air conditioning is to provide people with sufficient fresh air and a comfortable temperature. When exactly this “thermal comfort” level has been achieved in a bus, for example, is not so easy to determine, as Fabio Widmer states in the ISOTHERM final report: “The thermal comfort of an individual person is ultimately not an objective value that can be fully captured by quantitative values such as temperature.” For this reason, most models make statements about an expected “mean value” of the thermal comfort perception of a population.

To describe how good the thermal comfort is in a public transport vehicle, the ETH study drew on a model developed by Danish engineer Povl Ole Fanger a good 50 years ago. The model quantifies the thermal comfort perceived by people in a vehicle (or in a house) on a scale ranging from cold (-3) to hot (+3). This numerical value – referred to as Predicted Mean Vote/PMV – reflects the average subjective perception of warmth of a group of people. A value of +1, for example, means that people perceive a certain indoor climate as slightly too warm on average.

The PMV is calculated on the basis of the following influencing variables: Ambient air temperature, mean radiant temperature (of the sun, but also of surrounding surfaces such as cold windows or warm infrared heating elements,) physical activity, insulation value of clothing, air velocity, and relative humidity. Based on the PMV index, Fanger›s model also predicts the percentage of people in a group who would be dissatisfied with a particular thermal environment (Predicted Percentage of Dissatisfied /PPD.)

The following example serves as an illustration: An ambient air temperature of 15 °C and a mean radiant temperature of 14 °C at a humidity of 40 % leads to a PMV of -1 (slightly cool) and a PPD of 26 % with a slight draft of 0.1 m/s, winter clothing (1.3 clo) and no physical activity (sitting). That is, a group of bus travelers would find this situation slightly cool on average (PMV -1). Around a quarter of the group would be dissatisfied with the heating of the bus (PPD 26 %).



The study by ETH doctoral student Fabio Widmer (left) was supervised by Christopher Onder (right), ETH professor at the Institute of Dynamic Systems and Control. Photos: ETH Zurich

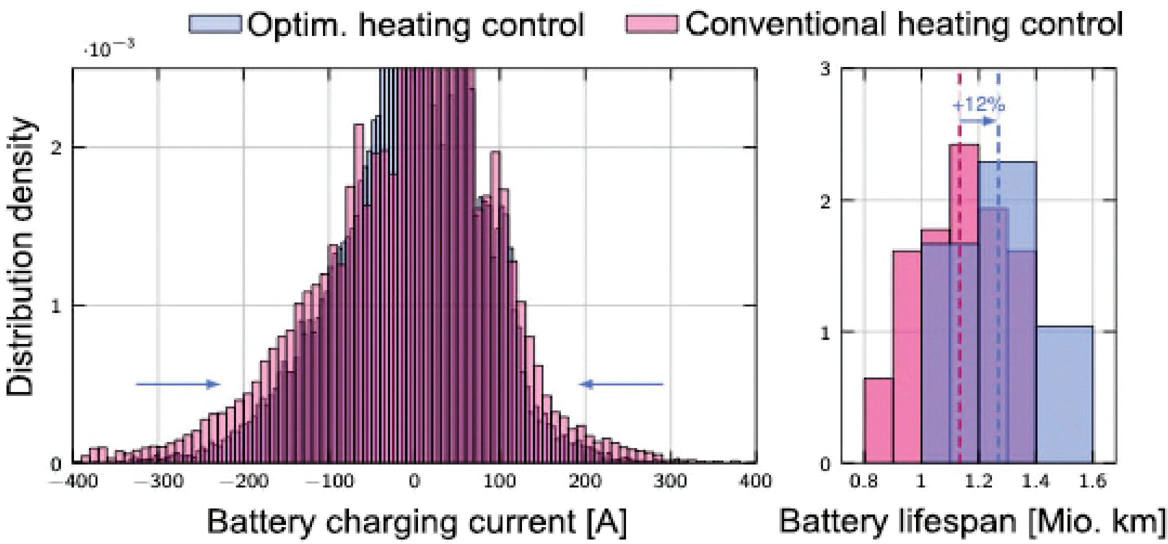
climates and relate them to passenger comfort requirements. Widmer›s model displays the influencing variables graphically and thus provides an understanding of how they affect each other.

An important result of the model calculations: If a heat pump is used instead of an electric heater to heat the passenger compartment, energy savings of 40 to 60 % can be achieved, depending on the vehicle type (see Figure p.3). The use of heat pumps, as is increasingly being practiced in modern buses and trains, therefore makes sense in terms of energy. The study also considers "very promising" so-called "door air curtains," i.e., curtains made of compressed air that reduce heat losses when doors are open. With such systems, which are only available as prototypes so far, it is estimated that the energy consumption of the HVAC systems in an articulated bus could be reduced by around a quarter. However, this calculation does not yet include the energy required to generate the air curtain.

Infrared radiators are not a promising addition

For vehicles in which doors are used less often than in buses, door air curtains are less recommended. In trains, for example, the ETH study suggests that increased energy efficiency could be achieved by improving the insulation of the passenger cabin. The study comes to a sobering conclusion when it comes to the use of radiant heat: Infrared radiators can be mounted on the cabin ceiling, which would directly supply passengers with heat without noticeably warming the air. The air temperature in the passenger cabin could thus be lowered without sacrificing comfort, thus saving energy. However, the model calculations in the ISOTHERM study show that infrared radiators in modern buses equipped with heat pumps do not bring any significant efficiency gains.

ISOTHERM has in the meantime been absorbed into a successor project, "Swiss eBus Plus." In this project, a long-range regional battery-operated bus is to be developed by 2026 in collaboration with ETH Zurich, Bern University of Applied Sciences, Carrosserie HESS and VBZ. The vehicle should be able to handle an entire day of operation without recharging. In addition, the HVAC systems are to run on battery power all year round, i.e., without the additional diesel heating that is still often required today. Achieving this goal will require the



The graphic on the left shows that the heating control system developed at ETH can reduce high charge and discharge currents. This benefits battery life (graph on the right). Graphic: ISOTHERM final report right choice of technical components, good insulation of the passenger compartment and optimal control of the energy supply. The SFOE is supporting the project with funds from its P+D program.

- The **final report** on the project ISOTHERM - Intelligent Software for Thermal Energy Management is available at: https://www.aramis.admin.ch/Texte/?ProjectID=44962

- For further **information**, please contact Luca Castiglioni (luca.castiglioni@bfe.admin.ch), Head of the SFOE Mobility Research Program.

- Further **technical papers** on research, pilot, demonstration and flagship projects in the field of mobility can be found at www.bfe.admin.ch/ec-mobilitaet.

Author: Benedikt Vogel, on behalf of the Swiss Federal Office of Energy (SFOE)
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