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# Potential of In-Motion Charging Buses for the Electrification of Urban Bus Lines

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## Abstract

Electric buses can help to reduce energy consumption, greenhouse gas emissions, pollutants and noise. One possible electric bus concept is the in-motion charger. As a combination of a trolleybus and a battery electric bus, the in-motion charger is able to operate relevant stretches in battery mode and therefore the amount of installed catenary wires can be significantly reduced. As a part of the German 'Mobility and Fuels Strategy' [2], the aim of the article's underlying work was to identify possible applications for the in-motion charger. This included a comparison of the environmental and economic performance of the different traction systems of urban buses (in-motion charger, opportunity charger, overnight charger, fuel cell hybrid and diesel buses). The analysis focused on an urban bus line, running with articulated buses and is covering the whole lifespan of vehicles and infrastructure. The analysis showed that in a lifetime perspective all electric systems can significantly reduce greenhouse gas emissions compared to buses fueled with fossil diesel. But even until 2025 the diesel bus will be the most economic bus technology under the assumed framework. In comparison with other electric buses, the in-motion charger is the most cost-effective bus system for high capacity lines.

**Keywords:** electric mobility, buses, environmental impact, economic analysis.

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# 1 Introduction

Public transport buses play an important role in urban mobility. Already today buses are reducing transport greenhouse gas emissions due to the shift from private cars. But for the long term goal of a climate neutral economy also public transport has to abandon fossil fuels and switch to renewables. The direct usage of electricity is the most energy efficient way of using renewable power.

Therefore electric buses are again on the agenda of decision makers (e.g. reflected in Hamburg's goal to stop the purchase of conventional buses in 2020): They can help reduce energy consumption, greenhouse gas emissions, pollutants and noise. Furthermore, they can support the introduction and integration of renewable energy sources and thus promote a diversification of energy sources. One possible electrification option is the In-Motion Charger (IMC). In contrast to a conventional trolleybus with electric auxiliary unit the battery of an IMC has a considerably higher capacity. This allows the IMC to operate relevant stretches in battery mode. Therefore the amount of installed catenary wires can significantly be reduced.

Goal of the study as part of the German 'Mobility and Fuels Strategy' [2] was to identify possible applications of the IMC and the resulting IMC's environmental benefit. The main steps were an in-depth analysis of the environmental and economic performance of the different electric bus systems (IMC, opportunity charger, overnight charger, fuel cell battery hybrid and diesel buses) followed by two workshops with stakeholders to identify usage and acceptance constraints.

# 2 Method

The comparison of the environmental performance is based on a detailed Life Cycle Assessment (LCA) (see figure 2). The functional unit is a bus kilometre or a passenger kilometre. The analysis focused on the production and the use phase of the bus. The global warming potential ($CO_{2\text{-eq}}$) is calculated including the emissions of carbon dioxide, methane and nitrous oxide. The assessment of pollutants is focusing on nitrogen oxide ($NO_x$) and particle mass (PM) emissions, which are currently most debated in respect to the compliance with European air quality standards.

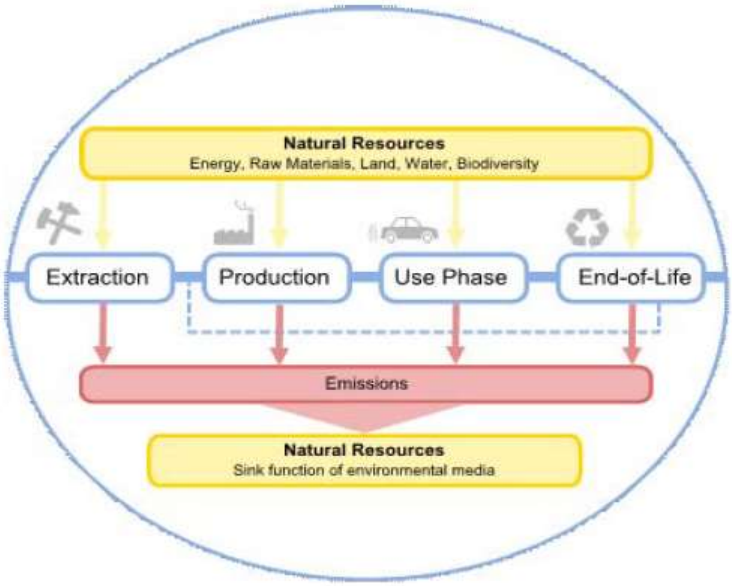


Figure 1: Schematic of LCA approach [7]

### 2.1 Use case

The drivetrain concepts are compared for an articulated bus (length ~18 m) on an urban line with an annual mileage of 60,000 km. These buses are widely used in Germany, particularly on lines with high passenger demand. The characteristics of the use case are chosen to represent an average German urban line with a length of 15 km in easy urban traffic (Standardised On-Road Test cycle (SORT) 2). Bus intervals from 15 to 4 minutes are examined which leads to a line capacity from 560 to 2,100 passengers per hour and direction (pphd). The technical details of the buses are shown in table 1:

Table 1. Technical parameters of compared electric bus concepts (articulated buses).

| **Power train parameter** | | **IMC** | **OC** | **ONC** | **FC** |
|---|---|---|---|---|---|
| Battery capacity | kWh | 70 | 150 | 400 | 30 |
| Power (engine, power electronics) | kW | 250 | 250 | 250 | 250 |
| Average charging power | kW | | 250 | 80 | |
| Fuel cell power | kW | | | | 160 |
| Hydrogen storage | kg | | | | 35 |

IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

Electric bus systems need proper infrastructure, but economic (lean) infrastructure and operational performance are often a trade-off. For this study, the infrastructure has been dimensioned after intense discussions with technology suppliers and public transport consultants.

Table 2. Energy supply infrastructure for different electric bus systems, example for 7.5 minute interval (15 buses/ line)

| | Infrastructure | Scale | Number |
|---|---|---|---|
| IMC | Catenary (two-sided) | | 7.5 km (50 % of the line) |
| | Substation | 750 kW | 4 |
| OC | Fast charging point (including substation) | 300 kW | 4 |
| | Charging point depot | 25 kW | 15 |
| | Substation depot | 400 kW | 1 |
| ONC | Charging point depot | 100 kW | 15 |
| | Substation depot | 1.5 MW | 1 |
| FC | Hydrogen refuelling station | Middle sized station | 25 % degree of capacity utilization |

IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

**2.2 Energy consumption**

The total consumption of the different power train concepts reflects the following losses and consumers:

- The energy of the engines to provide traction energy,
- the energy for the operation of auxiliary equipment (e.g. heating),
- the losses in the provision of energy (e.g. in charging infrastructure) and
- the losses in the vehicle (e.g. charging and discharging of batteries, losses in power electronics).

The energy consumption without heating/ air-conditioning was determined by Belicon GmbH at HAW Landshut using extensive measurements on different buses (see http://belicon-forschung.jimdo.com/). The consumption of heating or air-conditioning of electric buses could not be determined from measurements as this would have required year-long testing in different climatic conditions. Moreover, the majority of the vehicles measured were equipped with chemical auxiliary heaters, which are not part of the case study. Therefore, the consumption for heating/ air-conditioning had to be modelled. Major data input for modelling were:

- The Test Reference Years (TRY) of the 'Deutscher Wetterdienst'[4];
- The heating/ air-conditioning energy need of a bus as a function of the temperature difference between outside and inside[5];
- the efficiency of a heating/ air-conditioning system consisting of a combination of a heat pump and a heating resistor dependent on outside temperature and heating/ cooling demand.

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[4] see http://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html?nn=507312

[5] www.spheros.de/Media/Documents/3680/ HVAC%20in%20E-Bussen.pdf

### 2.3 Emission factors (exhaust and upstream emissions of energy carriers)

Tailpipe emissions of conventional buses are calculated using the 'Handbook Emission Factors for Road Transport (HBEFA, version 3.2)' database. The use phase emissions of electric buses are determined by the electricity production. The electricity production mix is based on work of the AG Energiebilanzen[6], Bundesverband Erneuerbare Energien (German Renewable Energy Federation)[7] and Fraunhofer Institut für Solare Energiesysteme (Fraunhofer Institute for Solar Energy Systems)[8]. Future electricity mixes are based on the Leitstudie 2011's 'Scenario A' [1]. The calculated emission factors for electricity production include the emissions of power plants and the supply of the primary energy carriers.

Table 3. Upstream emissions for different energy carriers

| | **$CO_{2\text{-}eq}$ [g/kWh]** | | | **$NO_2$ [g/kWh]** | | | **$PM_{10}$ [g/kWh]** | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Diesel | El | $H_2$ | Diesel | El | $H_2$ | Diesel | El | $H_2$ |
| 2015 | 58 | 584 | 381 | 0.14 | 0.62 | 0.33 | 0.01 | 0.16 | 0.03 |
| 2025 | 62 | 355 | 175 | 0.14 | 0.44 | 0.14 | 0.01 | 0.08 | 0.01 |
| EL = Electricity | | | | | | | | | |

### 2.4 Production emissions

To determine the environmental impact of bus production an LCA model for buses with different power train concepts has been developed. For the comparison of the different technologies the buses have been broken down into their essential components, as shown in figure 3.

The component approach allows for individual accounting of vehicles with different drive concepts. The LCA model contains detailed information for each component in respect to material input, production energy and transportation effort. The background data to for the material upstream-emissions is taken from the ecoinvent database (version 3.1).

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6 Working Group on Energy Balances, http://www.ag-energiebilanzen.de/4-1-Home.html
7 http://www.bee-ev.de/english/
8 https://www.ise.fraunhofer.de/en?set_language=en

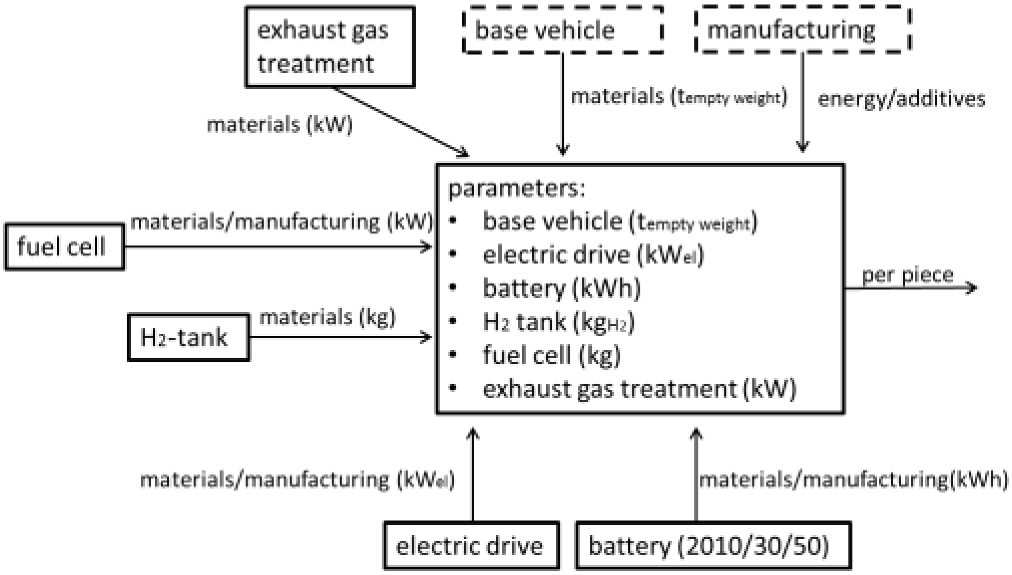

Figure 2: Schematic representation of the LCA model for bus production

In this work the emissions of the infrastructure could only be estimated roughly, as there is a lack of primary data on this topic. However, the available data show that the emissions for the construction of electric bus infrastructure should not exceed 80 g $CO_{2\text{-eq}}$/Bus-km [3].

## 2.5 Cost analysis

The Life Cycle Costs (LCC) of an urban bus line comprises vehicles, infrastructure, replacement, drivers, energy as well as service and maintenance costs. All costs are calculated with the annuity method and an interest rate of 5 %. In the standard case, a 12 year service life and a 5 % residual value are considered. The assumed vehicle costs are calculated from the component's cost. Therefore, the derived costs are independent of the current market situation. The projection of future component costs is derived from learning curves, see table 4 for batteries and fuel cells.

Table 4. Battery and fuel cell costs (nominal in €, 2015)

| | | Source | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| Battery | €/ kWh | 2015: expert guess Prof. R. Pütz Development 2015 – 2030: [6] | 1,000 | 784 | 684 | 622 |
| Fuel cell | €/ kW | [4]: 'Production-at-Scale'-Scenario | 1,161 | 609 | 542 | 432 |

The infrastructure is depreciated of the whole lifespan and then has a residual value of zero. Maintenance costs are assumed to be 2 % of the investment costs.

Table 5. Infrastructure costs (nominal in €)

| Infrastructure | Unit | Costs [€] |
|---|---|---|
| Catenary (two-sided) | per km | 350,000 |
| Substation | per unit, 0.4 - 1.5 MW | 430,000 - 1,720,000 |
| Fast charging point (including substation) | per unit, 300 kW | 250,000 |
| Charging point depot | per unit, 25 kW | 15,900 |

# 3 Main Results: Energy Consumption and Emissions

This chapter contains the results of the LCA divided in the sections energy use, greenhouse gas emissions and pollutants.

## 3.1 Energy consumption

The 2015 energy consumption of the buses is derived from measured and modelled data (see chapter 2). The assumptions on the development of energy efficiency until 2025 are made based on interviews with manufactures.

Table 6. Average yearly energy consumption of articulated buses

| Drive train concept | | Unit | 2015 | 2025 |
|---|---|---|---|---|
| IMC | Electricity | kWh/km | 2.1 | 1.9 |
| OC | Electricity | kWh/km | 2.1 | 1.9 |
| ONC | Electricity | kWh/km | 2.4 | 2.2 |
| FC | Hydrogen | kWh/km | 4.8 | 4.5 |
| | *Hydrogen* | *kg/ 100 km* | *14.4* | *13.5* |
| Diesel | Diesel | kWh/km | 5.2 | 5.0 |
| | Diesel | *l/ 100 km* | *52* | *50* |
| IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid | | | | |

The average yearly energy demand for heating is 0.31 kWh/km and therefore less than 15 % of the overall energy demand. In winter it can be up to 50 % (4.7 MWh in January) in the coldest region of Germany and become an important factor for the dimensioning of batteries and charging infrastructure.

## 3.2 Greenhouse gas emissions

The greenhouse gas emissions of the bus production are shown in figure 4. All alternative concepts have increased emissions in the production phase compared to the diesel bus. They are highly influenced by the size of the batteries in the respective electric bus concept. But also fuel cell hybrid buses have significant higher emissions due to vehicle production. The higher emissions of the fuel cell bus are mainly due to the Carbon-Fibre-Reinforced Polymer (CFRP) used in the hydrogen tank and platinum used in the fuel cell. More efficient production processes for CFRP, the use of electricity with a higher share of renewable energy and a higher share of recycled platinum could reduce these environmental impacts in the future.

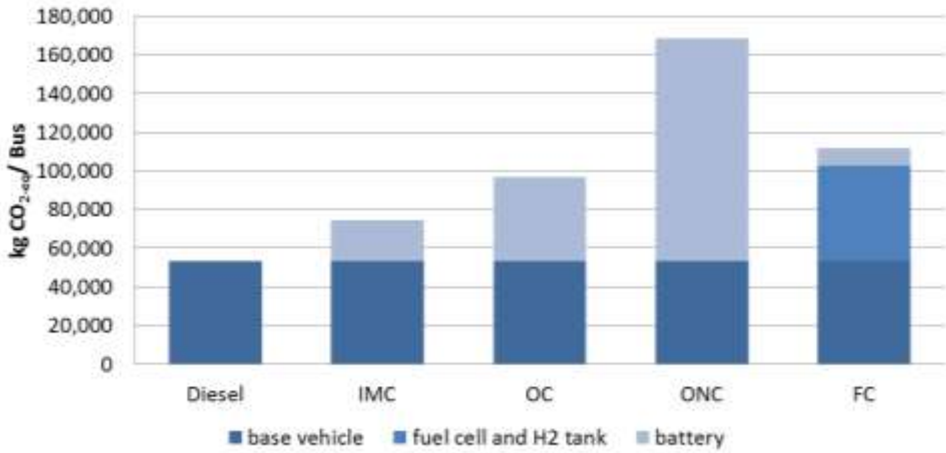


Figure 3: Greenhouse gas emissions per produced bus in 2015; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

For the sum of production and use phase all electrified concepts have lower greenhouse gas emissions than the diesel bus (see figure 5). With an increasing share of renewable energy in the electricity mix, the use phase emissions' benefit will increase to almost 40 % for the IMC and the opportunity charger. Overnight charger and fuel cell hybrid buses have significantly higher emissions due to higher production emissions and lower efficiency. Infrastructure construction emissions are negligible.

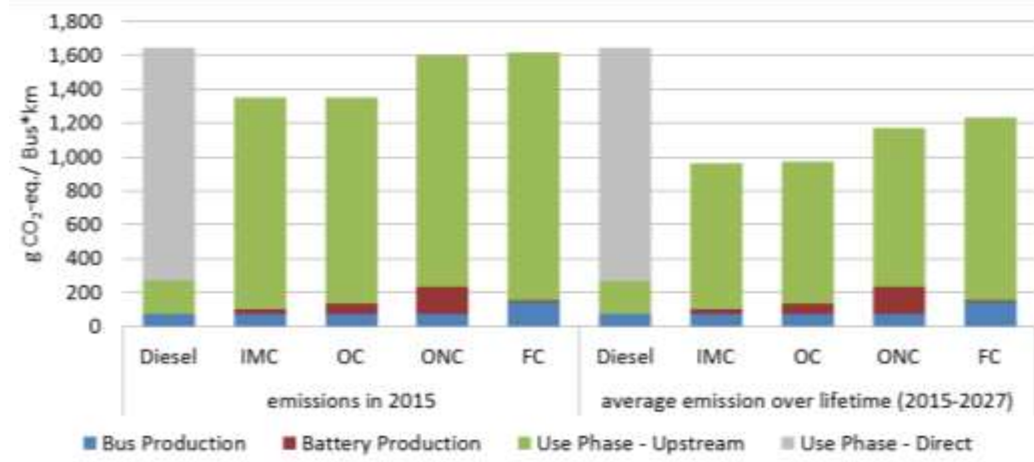


Figure 4: Production and in-use greenhouse gas emissions of different bus concepts in 2015; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

Comparing the situation with newly registered buses in 2015, all 2025 buses can increase their greenhouse gas advantage against the fossil fuelled diesel bus. This is partly due to improved components (batteries and fuel cells), but mainly due to the raising share of renewables in the energy mix. In contrast, the diesel bus has a slight increase in emissions due to a raising share of unconventional oil.

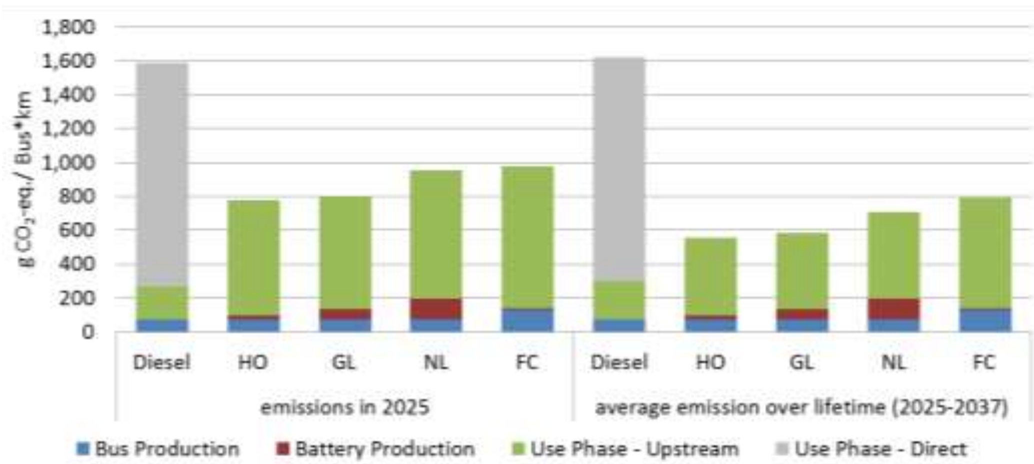


Figure 5: Production and in-use greenhouse gas emissions of different bus concepts in 2025; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

### 3.3 Nitrogen oxide and particle mass emissions

It is expected that NOx and PM emissions of diesel buses will decrease with the introduction of the Euro-6 standard, but electric buses are already local zero emission vehicles. This is in particular relevant, as the EU air quality directive

(Directive 2008/50 / EC 'Clean Air for Europe') is violated in many cities in Germany.

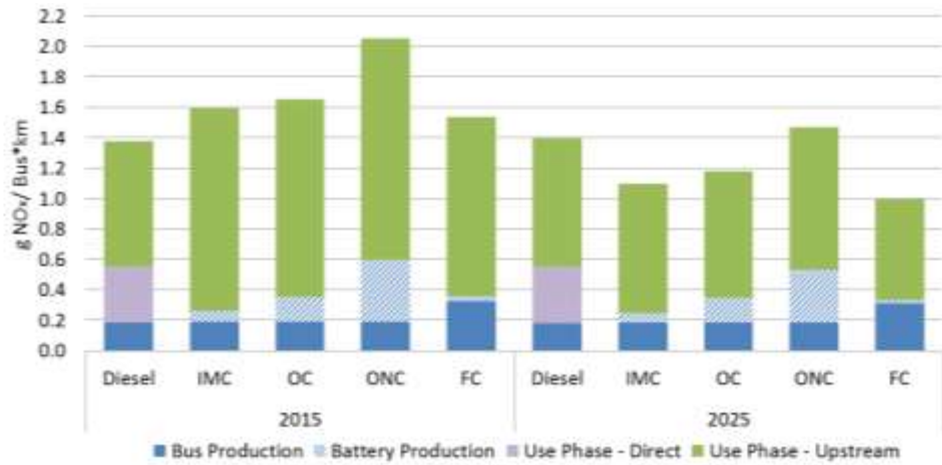


Figure 6: Nitrogen oxide emissions for different drivetrain concepts in urban buses; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

But zero local emissions in total are overcompensated by higher upstream emissions, which, however, mainly arise outside the urban areas. The electricity production (particularly for the electric buses in the use phase) could still lead to higher background pollution. Until 2025 the electricity mix is becoming cleaner and the environmental impact of battery production is decreasing (see figure 8).

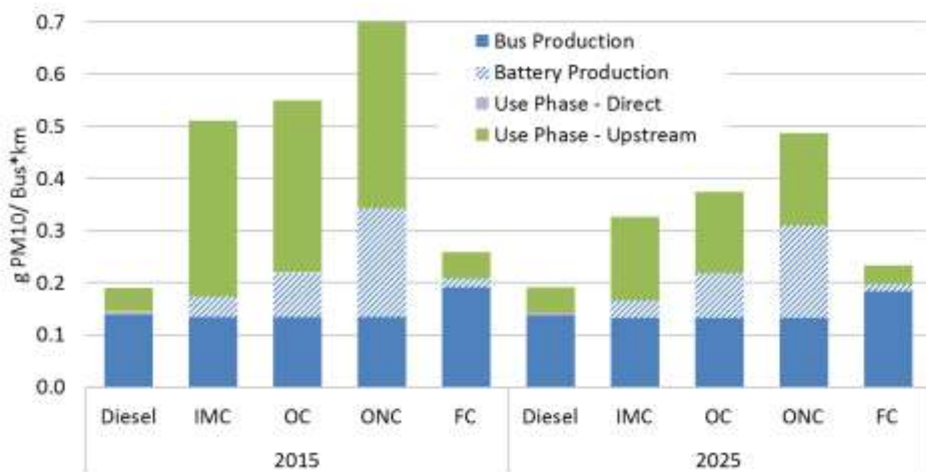


Figure 7: Particle emissions for different drivetrain concepts in urban buses; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

# 4 Main Results: Life cycle costs

The results of the vehicle's cost analysis are illustrated in figure 9. The vehicle costs are calculated based on the costs of the individual components in order to improve the comparability and on a projection of the future development of costs. It shows that in large-scale production bus prices could significantly lowered against today's market prices (actual market prices in 2015 are approximately 100,000 € higher than calculated costs).

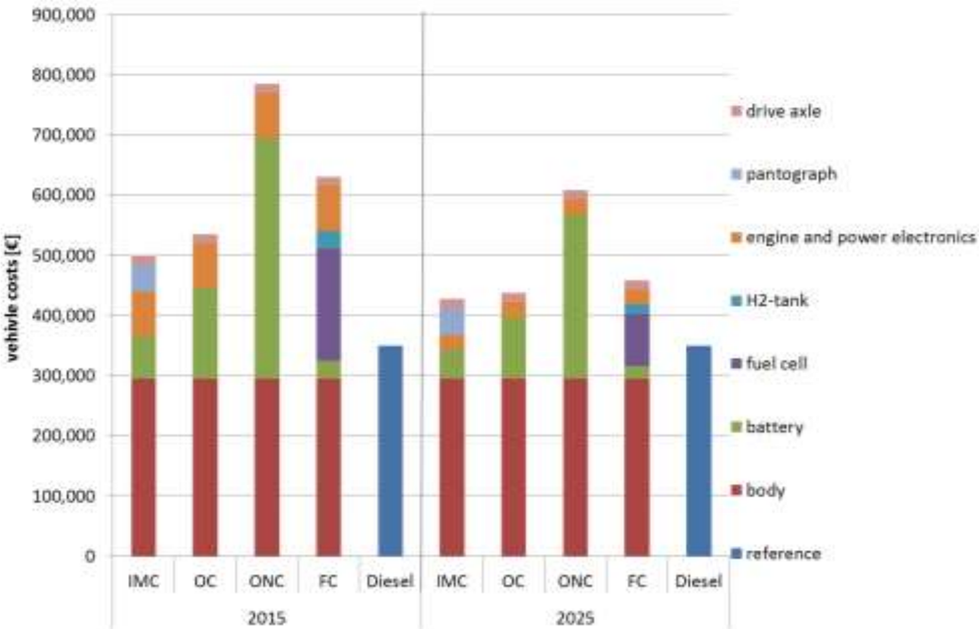


Figure 8: Vehicle costs of different power train technologies in 2015, 2025; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

The IMC's infrastructure costs are significantly higher than for the other bus concepts and therefore have to be considered in the economic analysis. The main parameters influencing the share of infrastructure costs at the IMC's LCC are the interval and the catenary system costs:

- While the infrastructure costs are independent from the interval, energy, driver and vehicle costs are increasing nearly linear (see figure 10). Therefore, the cost share of infrastructure is largely dependent on the interval, from 7 % in a 5 minute to 13 % for a 10 minute interval.
- The costs for the catenary system depend on its length and the specific costs. For an economic configuration of the catenary system it is favourable to choose sections with slow speeds (allowing longer charging time with shorter catenary length). Also, the specific costs per length can be lowered choosing sections with a low demand for superstructure.

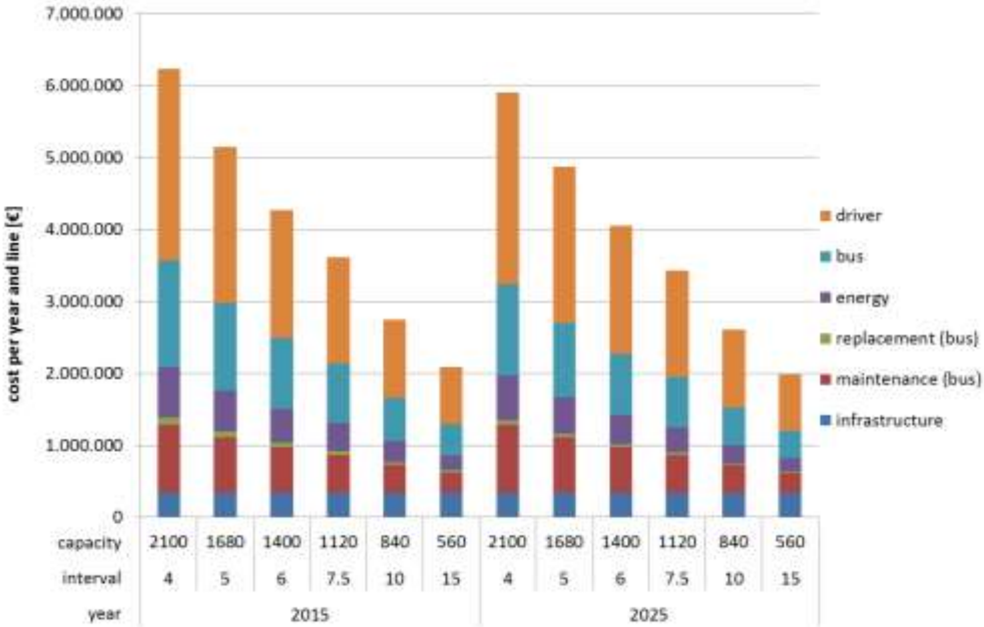


Figure 9: Costs per IMC bus line in 2015, 2025 for different intervals

Today the IMC has additional costs compared to a diesel bus of about 495,000 € per line and year for a ten minute interval (22 % cost difference per capacity). Compared to other electric buses, it is the most economical bus for below ten minute intervals (more than 1,100 pphd) (see figure 11).

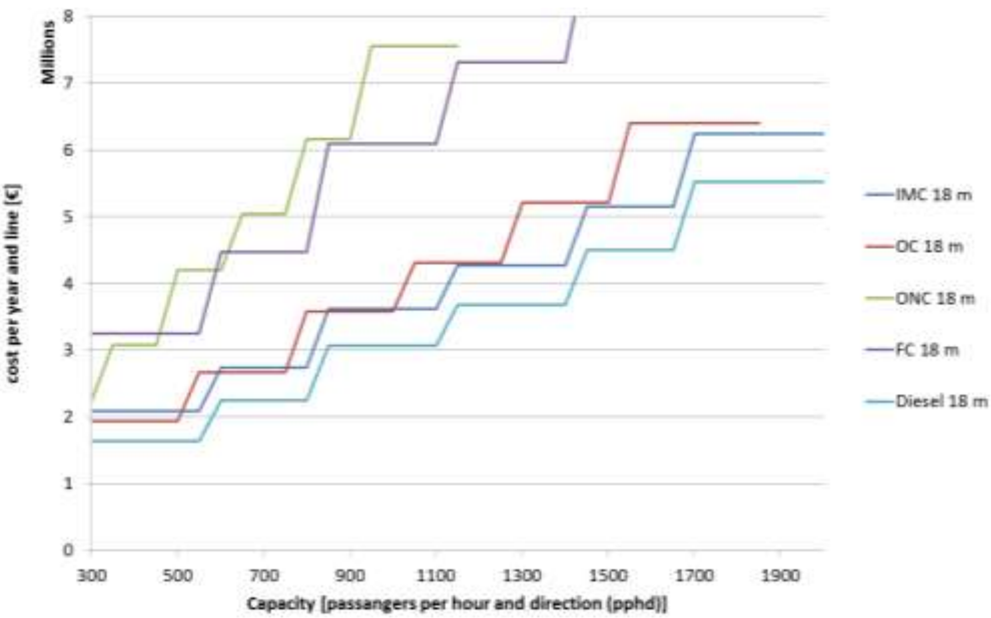


Figure 10: Costs per capacity in 2015; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

IMC's higher infrastructure costs can be compensated through lower vehicle demand and lower vehicle costs compared to overnight and opportunity chargers. Higher vehicle demand in case of overnight and opportunity chargers derives from following aspects:

- The overnight charger's higher battery mass is reducing the payload leading to a lower capacity per bus. Therefore more vehicles and drivers are needed. As the driver is the largest cost position in operating a line with at least 39 % share of total costs, higher driver demand can significantly lower economic performance. In 2015 the capacity costs for the overnight charger are twice as high as for the IMC (10 minute interval/ 92,000 pphd).
- The opportunity charger requires sufficient turnaround time to ensure minimum charging even under heavy traffic conditions. [5] shows that in the example of the City of Münster for about 40 % of the lines this leads to an increase in the scheduled turnaround time. This can lead to a higher number of vehicles and drivers needed for a line (see figure 12). In addition to the results shown in figure 12, three additional minutes turnaround time could lead to additional costs compared to the IMC of 92,000 € per year in a ten minute interval in 2015.

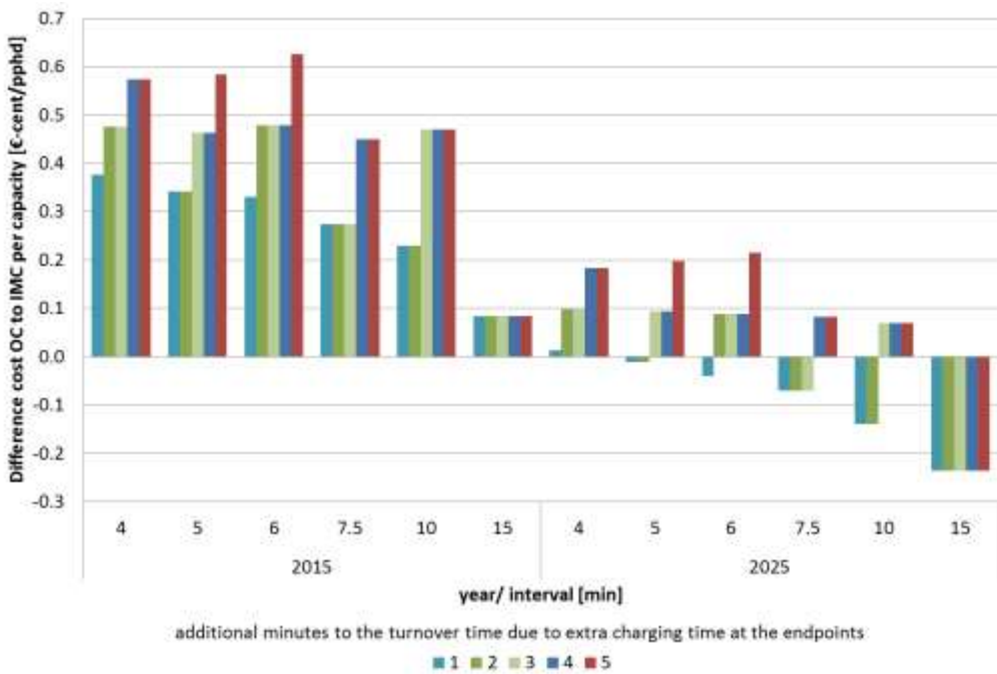


Figure 11: Additional costs of the opportunity charger (OC) compared to the IMC dependent on extra turnaround time for the OC in 2015 and 2025

With advances in battery technology (costs, energy density) until 2025 the LCC per capacity for the different electric concepts is converging (see figure 13).

Technologies without trackside infrastructure (fuel cell hybrid, overnight charger) are remaining more expensive than those concepts with trackside infrastructure (IMC, opportunity charger). For a wide range of possible use cases, the costs of IMC and opportunity charger are becoming almost equal. Urban design aspects and operational performance are becoming more important. The IMC will stay the most economical electric bus concept for high capacity until 2025.

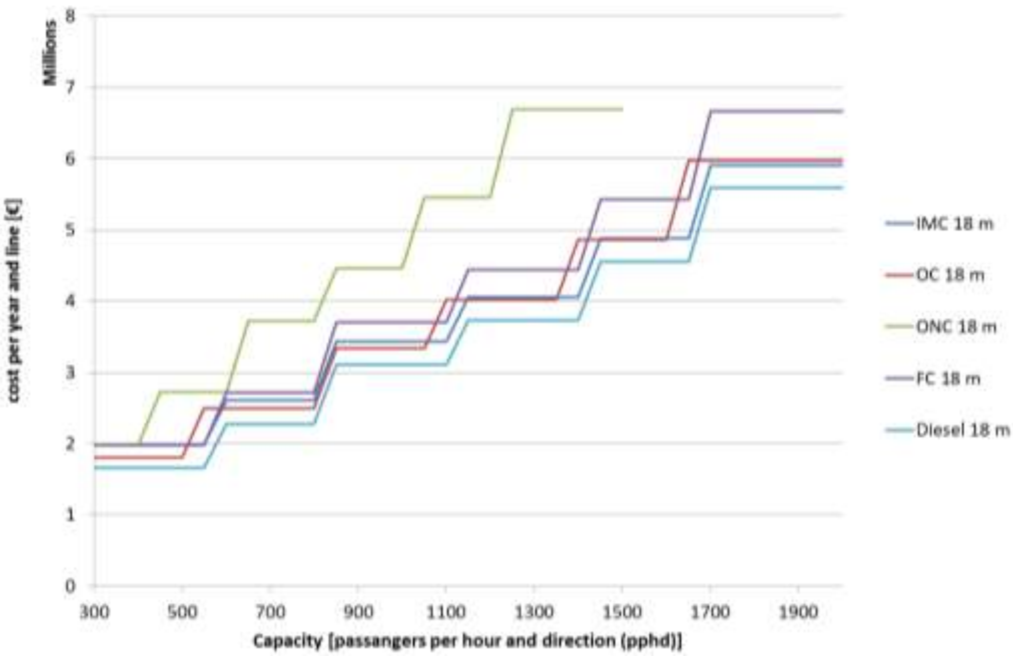

Figure 12: Costs per capacity in 2025; IMC = In-Motion Charger, OC = Opportunity Charger, ONC = Overnight Charger, FC = Fuel Cell Hybrid

## 5 Potential of In-Motion Charger Buses

In this chapter the results of the analysis are mirrored to the situation of public transport in Germany. The chapter will give a short overview about mitigation obstacles for the IMC and current trends in the public transport sector.

### 5.1 Economic situation

Funding for public transport is severely limited in Germany; especially the municipalities are not in a position to transact larger investments. Therefore, local public transport remains on the status quo, as long as investments are not funded in large parts by the federal states and/ or the federal government. In almost all counties there are already incentive programs for electric buses. For the economic viability of the IMC the inclusion of the infrastructure in these programs is crucial. The economics of IMC are much more attractive, if compared to a tram instead of a diesel bus. This has to be seen in the light of the ongoing establishment of double-articulated buses in various European cities. Due to the low number and the legal restrictions of double-articulated buses in Germany, they were not in the focus of this investigation. However, with the results of this study they seem to be an ideal field of application for IMC and being significantly more economic than trams for a wide range of applications.

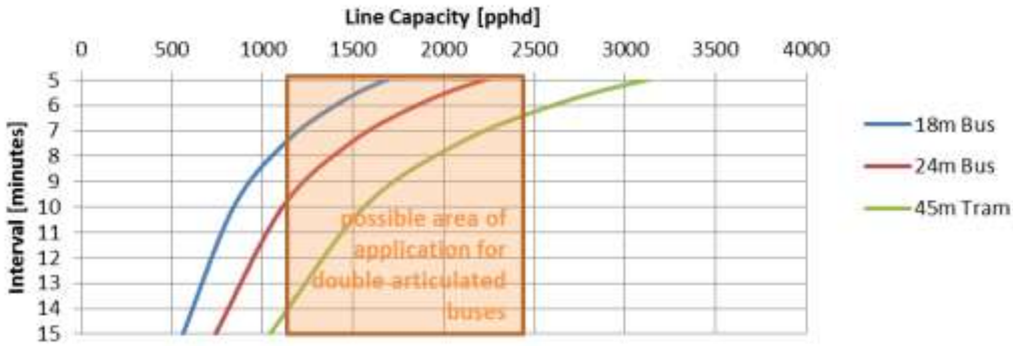


Figure 13: Capacity of public transport systems dependent on type of vehicles and service interval (18 m articulated bus - 140 places, 24 m double articulated bus - 185 places, 45 m tram - 260 places)

**5.2 Implementation efforts**

Particularly for the public transport operator, the change to IMC's is accompanied by some efforts. The most relevant are:

- Complex operations due to the presence of several different drive train systems (at least in the transition phase).
- Changing job profiles to the employees. Therefore, extensive training is needed for a generally older workforce. Also the recruitment of highly skilled mechatronics is challenging because of competition with the automotive industry. This effort can be smaller if the public transport operator is already using electric means of transport like tram or light rail.
- Termination of established manufacturer relations if the usual supplier does not offer IMCs. Today, the only company with a relevant market share offering IMCs in Germany is Solaris. Currently, there is no German manufacturer offering IMCs.

# 6 Conclusion

Our analysis shows that a diesel bus running with conventional diesel remains the most economic technology until 2025 as long as the regulatory framework remains unchanged. But it contributes very little to the central goals of the German 'Mobility and Fuels Strategy' (MFS), like the reduction of energy consumption and greenhouse gas emissions or the introduction of new technologies. In contrary, electric buses could significantly contribute to these goals. With progress in the energy transition (‘Energiewende’) and the further development of battery technology electric buses will become more beneficial, particularly from the environmental point of view. For electric buses, the IMC is seen as the most economical technology for high capacity lines (frequent service, high capacity vehicles) or lines with a high energy demand. Therefore, the IMC is seen as an essential part of an electrification strategy for urban public transport.

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